Report No. CG-D-07-97

Portable Emissions Testing of a 105-FT Commercial Tug

Alan Bentz
Bert Macesker
Robert Desruisseau

U.S. Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

FINAL REPORT
October 1996

Prepared for:

U.S. Department of Transportation
United States Coast Guard
Systems, (G-S)
Washington, DC 20593-0001

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

The contents of this report reflect the views of the Coast Guard Research & Development Center. This report does not constitute a standard, specification, or regulation.

G.T. Gunther
Commanding Officer
United States Coast Guard
Research & Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-07-97		

4. Title and Subtitle	5. Report Date
Portable Emissions Testing of a 105-FT Commercial Tug	October 1996
	6. Performing Organization Code
7. Author(s) Alan Bentz, Bert Macesker, Robert Desruisseau	8. Performing Organization Report No. R&DC 28/96
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, Connecticut 06340-6096	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation United States Coast Guard Systems, (G-S) Washington, DC 20593-0001	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code Commandant (G-SEN) USCG Headquarters Washington, DC 20593-0001

15. Supplementary Notes

The R&D Center's technical point of contact is Bert Macesker, 860-441-2726.

16. Abstract

Emission testing was conducted in May 1996 on a commercial tug as part of a general Coast Guard R&D study to evaluate protocols for shipboard emissions testing. The objectives of this test were to determine emissions data for a commercial tug, evaluate fuel savings techniques, and evaluate portable testing protocols for emissions testing. Portable emission analyzers were used that employ electrochemical sensors. The NOx values determined were below both the International Maritime Organization's (IMO) and Environmental Protection Agency's (EPA's) maximum allowable levels for a 1225 RPM rated engine. A commercial engine speed pilot was installed with a fuel management system to record fuel consumption, engine horsepower, and provide a capability of balancing the engines for optimum running efficiency. An indication of fuel savings was apparent when the engine speed pilot was engaged.

17. Key Words	18. Distribution Statement
emissions fuel savings engine speed pilot	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. SECURITY CLASSIF. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

METRIC CONVERSION FACTORS

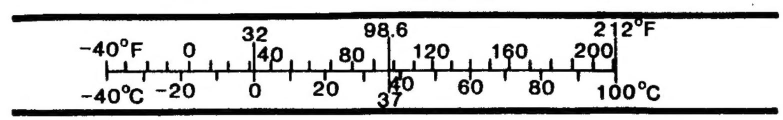
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

Emission testing was conducted in May 1996 on a commercial tug as part of a general Coast Guard R&D study to evaluate protocols for shipboard emissions testing. The objectives of this test were to determine emissions data for a commercial tug, evaluate fuel savings techniques, evaluate portable testing protocols for emissions testing, and also evaluate alternatives to measuring horsepower and fuel rate that would be more efficient and simpler than traditional approaches.

Testing was conducted on the Maritrans, Inc. Tug COUGAR which is a typical tug boat that is married to a notched fuel barge. In order to relate measured emissions data to ship physical and operating characteristics, several variables were measured which included shaft and engine horsepower, fuel consumption, turbocharger intake air flow, exhaust stream emissions, and diesel fuel constituents. Using a calculation procedure developed by the Coast Guard R&D Center, the average weighted NOx values for a number of tug operating configurations were determined to be,

Free Tug	→ 4.5 g/kWh (port engine)
Tug w/ light barge	→ 5.1 g/kWh (port engine)
Tug w/ full barge	→ 4.9 g/kWh (port & stbd engine average)

These NOx values are below the IMO maximum allowable level of 10.85 g/kWh for a 1225 rpm rated engine. They are also well below the EPA average criteria of 9.2 g/kWh.

A commercial engine speed pilot (analogous to an automobile cruise control) was installed with a fuel management system to record fuel consumption, engine horsepower, and provide a capability of balancing the engines for optimum running efficiency. A strong indication of fuel savings was apparent with the engine speed pilot engaged.

Two different portable emission analyzers were evaluated which employ electrochemical sensors. The ENERAC Model 3000E appears to give reliable NOx readings, based on its design to eliminate cross contamination, provide multiple sensor ranges, and absorption losses.

The tug boat test represents one of a series of several shipboard emission tests that are being conducted to gain experience and to collect data in developing a practical shipboard emission test protocol for recommendation to the International Maritime Organization. The last of the series of tests as part of the R&D project will be done on a Coast Guard Cutter construction tender (WLIC). The data and lessons learned from all of the tests will be used in constructing the shipboard emission protocol.

ACKNOWLEDGMENTS

Appreciation is expressed to Maritrans Inc. for the use of their Tug COUGAR. Special thanks to the crew of the Tug COUGAR for its cooperation and technical support during the test period. Although Jim Tabor from Smartboat, Inc. was responsible for the EMS-1000 fuel management system and ESP-1000 engine speed pilot instrumentation, he also provided invaluable support in the conduct of the overall test. Appreciation is also expressed to SCPO Brion of the R&D Center's Marine Systems & Environmental Technology Division for his technical assistance in collecting the emissions data.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

1 Background

1.1 Purpose of Test

This emission ship test supports the research on the development of portable emissions testing protocols for consideration by the International Maritime Organization (IMO). This effort has been conducted within the present Exhaust Emissions Project, 3310, at the Coast Guard Research & Development Center (CG R&D Center), sponsored jointly by the Naval Engineering Projects Division at USCG Headquarters, and by the U.S. Maritime Administration.

1.2 Review of Regulatory Actions

The U.S. Coast Guard's interest in emissions testing arises from its desire to meet all federal and state quality regulations and the fact that it may be called upon in the future to enforce regulations in the marine environment. In the U.S., the Clean Air Act Amendments of 1990, Section(a)(3), have charged the U.S. Environmental Protection Agency (EPA) with defining and controlling the emission inputs from non-road sources, including marine sources. On the international level, the IMO has developed proposed guidelines for controlling air pollution from ships. Additional discussion on regulatory actions, including proposed emission levels, can be found in Reference [1].

1.3 Prior Coast Guard Work on Portable Emission Measurements

Because of concern that laboratory bench testing does not duplicate the actual in-service load cycles on marine engines, and that performance of in-service engines degrades in time and their emissions increase, it is desired to measure emissions at-sea. There may be several modes of operation for vessels (duty cycles) with defined speed, torque, and time. ISO 8178 lists several duty cycles in Reference [2]. EPA recommends cycle E2 at four different torque values (as a percentage of full torque), giving emissions as a weighted average of the four values.

The CG R&D Center conducted a series of tests involving three Point Class 82-FT patrol boats using ISO 8178 procedures in Reference [3]. Six Coast Guard cutters and patrol boats were also tested for emissions by Environmental Transportation Consultants (ETC) in Reference [4]. The purpose of these tests was to survey vessel emissions to provide the Coast Guard with a database for air quality compliance planning and to update the emission inventory for selected USCG vessel classes operating under the jurisdiction of California Air Resources Board (CARB). The CG R&D Center and Maritime Administration recently conducted testing (Reference [1]) on the M/V KINGS POINTER to quantify the level of pollutants and to further explore portable emissions testing technology for shipboard applications.

2 Introduction

2.1 Objectives

The objectives of this test were to:

- determine emissions data for a commercial tug
- evaluate portable testing protocols for emissions testing including the evaluation of alternatives to measuring horsepower and fuel rate that would be more efficient and less cumbersome to instrument
- evaluate fuel savings techniques

2.2 Tug COUGAR Description

The commercial tug was selected for testing in a meeting between Dr. Bentz of the CG R&D Center and Mr. Dittrich of Maritrans, Inc. during Propulsion '95 in New Orleans. Maritrans, Inc., being very interested in emissions research, offered the use of one of its tugs for emissions testing. The Maritrans, Inc. Tug COUGAR is a typical tug boat that is married to a notched fuel barge. The tug and barge usually make transits between Carteret, NJ and Bridgeport, CT, delivering fuel to the tank farm at Bridgeport. The crew estimated making as many as three deliveries every week of the year. The Tug COUGAR's last dry-docking was April 1996, which was just before the emissions testing in May. The principal characteristics are presented in Table 1.

Table 1 Characteristics of Tug COUGAR

Tug COUGAR:	
Length Overall	105'
Beam	32'9"
Draft	15'3"
Vert. Clearance	70'
Gross Tons	171
Net Tons	116
Main Engines (2)	Caterpillar D399s
Red Gear	Reint Jes/WAV1400
Red Gear Ratio	5:1
propellers (2)	4 bladed
Ocean 60 Barge:	
Length Overall	310'
Beam	62'
Draft Light	3'6"
Gross Tons	3824

Coast Guard R&D Center staff from the Marine Systems & Environmental Technology Division and a Stellar Marine representative from Smartboat, Inc. were on-board the Tug COUGAR from 9 May through 16 May, 1996. The first two days, 9 and 10 May, were used for installing the test gear. Twelve hours were needed by both Coast Guard personnel and the Steller Marine representative to install the horsepower meters, the fuel management system (EMS-1000), and engine speed pilot (ESP-1000). Test data were collected whenever possible from 11 May through 15 May. On 16 May gear was removed and the test team departed.

2.3 Overview of Test Data and Equipment

Data Collected

In order to relate measured emissions data to ship physical and operating characteristics, several physical variables had to be measured. A complete discussion of the variables that affect engine exhaust emissions may be found in Reference [3]. Data listed in Table 2 were collected.

Table 2
Ship Test Data Collected

Barometric Pressure (inches of Hg)
Relative humidity near engine intake (%)
Temperature associated with relative humidity (°F)
Intake Air Temperature (°F)
Shaft rpm (port & stbd)
Engine rpm (port & stbd)
Shaft Horsepower
Fuel Flow (GPH)
Intake Air Flow (CFM)
Stack Temperature (°F)
Oxygen volume (dry) in exhaust (%)
CO volume (dry) in exhaust (%)
Excess Air Volume (dry) in exhaust (%)
NO volume (dry) in exhaust (ppm)
NO_2 volume (dry) in exhaust (ppm)
NOx volume (dry) in exhaust (ppm)

A discussion of how each variable was collected follows:

Barometric Pressure, Relative Humidity, Air Temperature

Barometric Pressure was recorded in the Maritrans Tug COUGAR's engine room on a Control Data digital recorder. Barometric pressure was also recorded by each of the

Shortridge Flowhoods[5] installed on the inboard port and starboard turbocharger air intakes. The Control Data digital recorder was checked against the University of Connecticut's Marine Science Institute equipment. Relative humidity, air temperature, and barometric pressure readings agreed within 4%. Relative humidity readings were checked against a Dickson Company Model THDx humidity sensor while in the engine room. Air temperature readings were taken from the Shortridge Flowhoods installed on each inboard turbocharger and were confirmed against temperature readings available on the Control Data digital recorder and THDx chart recorder. All of these data were recorded manually.

Shaft rpm/Engine rpm

Shaft rpm and shaft horsepower were measured with Coast Guard owned Wireless Data Corp. horsepower (HP) meters [6]. Engine rpm, by sensing the rotations of the flywheel gear, was recorded by the Stellar Marine fuel management system (EMS-1000) system. These data were recorded manually and also recorded continuously by the Stellar Marine EMS-1000 data logging software when functioning. The 5:1 reduction gear ratio was confirmed by the engine rpm readings recorded by the EMS-1000 and the shaft rpm measurements made with the Coast Guard instrumentation.

Shaft Horsepower/Torque - Shaft torque was measured on the port and starboard shafts with strain gauges during each test run. Shaft torque measurements were used in determining shaft HP. Each propulsion shaft was outfitted with a Wireless Data Corporation Model 1642A horsepower measuring system [6] which consisted of a strain gauge bonded to the outside of the shaft and a magnetic pickup which recorded the rpm. An FM transmitter collar system transmitted the strain information to the horsepower meter. The measured strain was converted to torque. Accuracy of the instruments were within 2% of full scale which was 1500 HP. Thus accuracy was +/- 30 HP.

Air Pressure, Temperature, and Humidity - These parameters were measured in the vicinity of the air intake. Flowhoods were attached to the turbocharger and provided air pressure and temperature as well as flow rate in cubic feet per minute (CFM).

Fuel Consumption - Fuel consumption was calculated and recorded by the EMS-1000 in gal/hr.

Exhaust Gases - Emission analyzers that employ electrochemical sensors recorded the composition of exhaust gases in ppm or percent concentrations. A probe was inserted through a fitting on the exhaust stack located less than two feet above the engine. Exhaust gas concentrations of CO, NO, NO_2, SO_2, O_2 were recorded manually by Coast Guard personnel and data streamed, in some instances, to the EMS-1000 for continuous data-logging. Two different analyzers were used including the ENERAC Model 3000E and ECOM-KD. The sensor's accuracy for NO, NO_2, and CO ppm readings on the ECOM-KD[7] and ENERAC 3000E[8] are advertised as 5% and 2%, respectively.

2.4 Portable Test Instrumentation Discussion

Figure 1 provides an overview of the instrumentation used on the Tug COUGAR. It was intended to use two ECOM-KDs. The EMS-1000 fuel management system was configured to record data from the ECOM-KD's RS232 ports. However, one of the ECOM-KD analyzers malfunctioned and was inoperable during the test period. During the test the ECOM-KD presented an alarm indicating that the NO sensor battery was low. Therefore, data were streamed to the EMS-1000 data logging software from one emission analyzer only. The other emission analyzer employed was the ENERAC Model 3000E. The ENERAC Model 3000E was recently acquired by the Coast Guard R&D Center through an upgrade of an ENERAC 2000E but was not supplied with an SO_2 sensor. Both analyzers were calibrated in accordance with [7] and [8] before the test and span gas readings were checked before and after the shipboard test with the following results:

Table 3 Instrument Readings after Test (originally calibrated to nominal span gas values)

	reading from tank (ppm)	ECOM-KD calibration	reading from tank (ppm)	ENERAC 3000 calibration
CO	815	751	625	751
NO	1120	1034	923	1010
NO_2	101	104	450	500
SO_2	470	512	-	-

In general, there appears to more disparity from the tank readings in the ENERAC 3000E post-test span gas readings than in the ECOM-KD. The final readings on the emission analyzers were made at the R&D Center about four days after the test was complete.

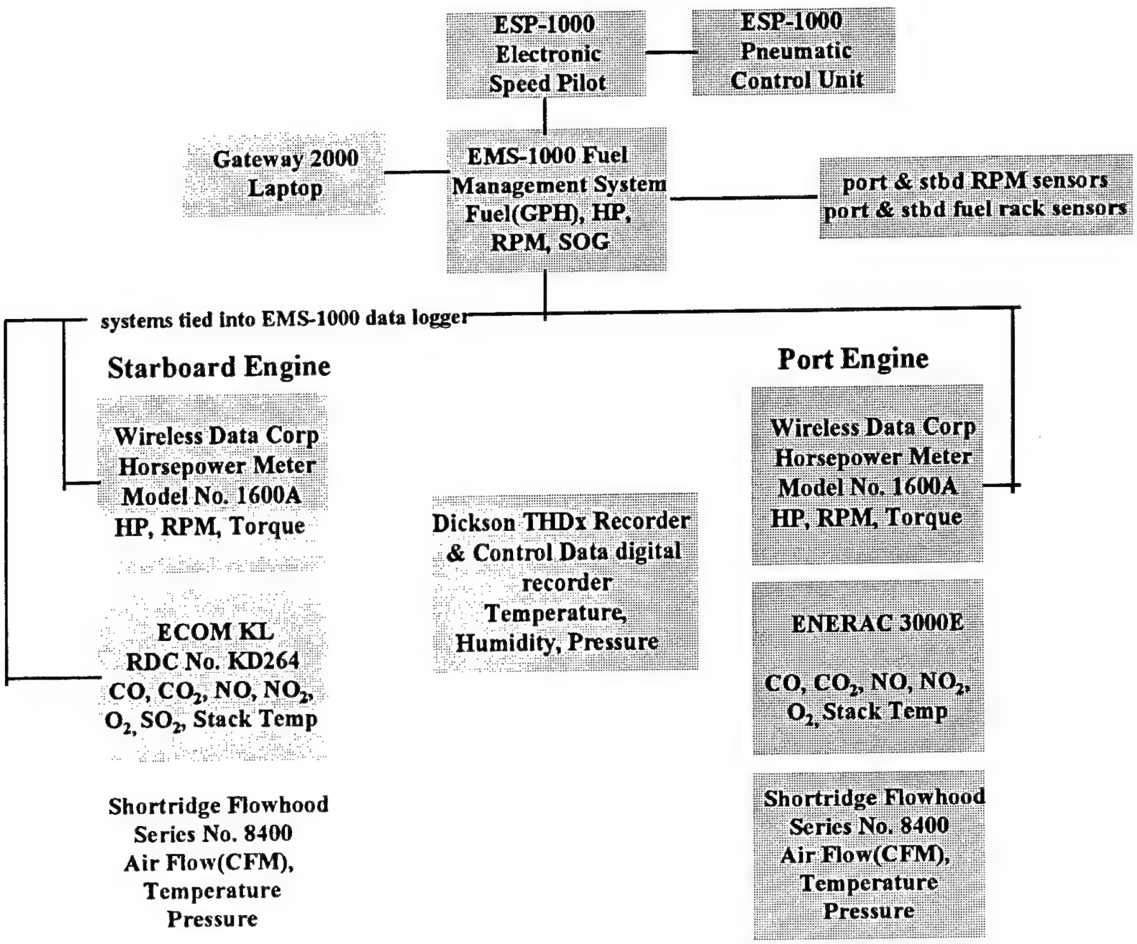


Figure 1 Overview of Tug COUGAR Instrumentation

Fuel measurement on diesel engines require that both the supply and return fuel lines be monitored to measure the net fuel flow that goes to the engine. In-service horsepower measurements using conventional methods of strain gauges on shafts require time consuming and laborious installation procedures.

The approach of measuring shaft horsepower using strain gauge installations has been the approach the R&D Center has employed for the last two decades when instrumenting various Coast Guard vessels for test & evaluation (T&E). This has proven to be a reliable and consistent approach over the years. It is, however, a time consuming and demanding procedure that requires a skilled technician. Meticulous care is taken to prepare the shaft for strain gauges as well as the system setup. This process can take from 12 to 24 hours depending on accessibility of the shafts.

An alternative means of determining in-situ horsepower of main diesel engines was developed by Stellar Marine Inc. Their method determines horsepower as well as fuel consumption based on the fuel rack positions. Both systems were used in testing the Maritrans Tug for comparative purposes. The premise behind the EMS-1000 in Reference [9] is that diesel engines are equipped with precise fuel metering systems. The fuel

injectors deliver a precise amount of fuel into each cylinder at specific intervals. The quantity and rate of fuel is determined by the settings on the engine rpm and fuel racks. The EMS-1000 measures fuel consumption using the engines own fuel metering system. The EMS-1000 Main Control Unit uses a patented algorithm to determine fuel rate and horsepower based on the fuel rack position, rpm, and engine manufacturer's test data. Engine rpm is determined with a magnetic pickup that senses and counts the number of flywheel teeth that pass by its position.

The Stellar Marine fuel management system (EMS-1000) was used to measure fuel consumption, speed, and HP. Fuel consumption was determined with a potentiometer that recorded the fuel rack position calibrated to fuel used. The Stellar Marine engine speed pilot (ESP-1000) was also installed and required tapping into the throttle pneumatic system. The ESP-1000 was purported to control the throttle in such a way as to balance the engine outputs and give more efficient operation with a resulting fuel savings of as much as 10-15% in some instances. Both the EMS-1000 and ESP-1000 software were installed on the Gateway 2000 laptop. The laptop was used to engage and disengage the engine speed pilot. Obviously, fuel savings are of great interest to both industry and the Coast Guard. The evaluation of the ESP-1000 was considered a secondary test which was to be accomplished on a not-to-interfere basis with the primary emission data collection.

Fittings were installed in the port and starboard exhaust stacks about a foot above the engine to accommodate ball valves. The ball valves were opened after steady-state stack temperatures were attained at which point the emission analyzer probes were inserted. The Shortridge Flowhoods were attached to the inboard port and starboard turbochargers with a hose clamp and suspended from overhead deck grates.

The test rpms to represent the four different operating points per ISO 8178 in Reference [2] were determined on 11 May. A maximum speed run was conducted with the tug by itself to determine a top port and starboard average rpm. This was determined to be 1178 rpm. Based on this value the test rpms were determined as:

100% → 1178 rpm	corresponding to	100% power
91% → 1072 rpm	corresponding to	75% power
80% → 942 rpm	corresponding to	50% power
63% → 742 rpm	corresponding to	25% power

3.0 Test Results

3.1 Tug Pushing Full Load Barge

Testing was conducted with the Tug COUGAR pushing a full barge on 15 May while making a fuel delivery from Carteret, NJ to Bridgeport, CT. Table 4 presents the order of test runs conducted. The % corresponds to the percent of maximum rpm setting determined. The letter preceding the % rpm setting is a unique designator for a particular test configuration used for tracking in the data spreadsheets. In the case of the tug pushing

a full barge, a randomized test sequence was not attempted because of operational restrictions. A randomized test sequence of % rpm operating points in accordance with Reference [3] was conducted for the other tug configurations.

Table 4 Testing Run Sequence for Tug with Full Barge

(1)	(2)	(3)	(4)
F100%	-	H100%	G80%
F91%	E80%	H91%	G91%
F80%	E91%	H80%	G100%
F63%	E100%	H63%	IDLE

(1), (2) speed pilot off; ENERAC - stbd engine; ECOM - port engine
(3), (4) speed pilot on; ENERAC - port engine; ECOM - stbd engine

At convenient points in the test, the two emission analyzers were swapped between engines so that differences in analyzer readings could be evaluated.

Computations used to determine engine pollutant levels are based on a stoichiometric material balance of incoming fuel and air with exhaust. The basic assumption is that there is more than sufficient oxygen available in the air entering the diesel engine to affect complete combustion of the fuel components. For the material balance, the quantity of air per unit time (including water vapor), and the quantity of fuel per unit time account for all incoming materials. The material balance calculations to determine pollutant levels and manually recorded data for this test are presented in Appendix B. The calculations for the pollutant levels for the tug at idle are also presented in Appendix B.

3.2 Tug Pulling Light Barge

The Tug COUGAR was tested with the Ocean 60 barge under tow on 13 May enroute from Bridgeport, CT to Carteret, NJ. Table 5 presents the order of test runs conducted. The Shortridge Flowhood on the starboard engine gave erratic readings, sometimes as much as one-half the readings on the port flow meter. It was later determined that this Flowhood's charging system had malfunctioned. Therefore, the readings on the starboard engine were not used in the material balance to determine the weighted pollutant levels.

Table 5 Testing Run Sequence for Tug with Light Barge

(1)	(2)	(3)	(4)	(5)	(6)
B100%	D80%	A63%	C63%	B100%	A63%
B91%	D91%	A80%	C100%	B91%	A80%
B80%	D100%	A91%	C91%	B80%	A91%
B63%	D63%	A100%	C80%	B63%	A100%

(1), (2) speed pilot on; ECOM - stbd engine; ENERAC - port engine
(3), (4) speed pilot off; ECOM - stbd engine; ENERAC - port engine
(5), (6) speed pilot off; ECOM - port engine; ENERAC - stbd engine

The material balance calculations to determine pollutant levels and manually recorded data for this test are presented in Appendix C.

3.3 Free Tug

The Tug COUGAR was tested in the free condition, i.e., without towing or pushing the barge, on 14 - 15 May. Testing was done in the East River around Manhattan in the middle of the night to minimize encounters with vessel traffic. An attempt was made to randomize the test operating points. However, the order of testing was often switched because of traffic encountered in the East River. Table 6 presents the order of test runs conducted.

Table 6 Testing Run Sequence for Free Tug

(1)	(2)	(3)
A63%	B80%	C63%
A80%	A100%	C100%
A91%	B91%	C91%
B63%	B100%	C80%

(1), (2),(3) speed pilot off; ENERAC - stbd engine; ECOM - port engine

The Shortridge Flowhood on the starboard engine gave erratic readings, sometimes as much as one-half the readings on the port flow meter. Both Flowhood meters were sent back to Shortridge Instruments, Inc. for calibration after the test. The readings were found within specifications (+/- 3% +/- 5 CFM) on both meters. The erratic readings during the test are attributed to the low battery indicator light coming on periodically even though the unit was thought to be charged. Rechargeable batteries were replaced on both units after the test. Therefore, the readings on the starboard engine were not used in the material balance to determine weighted pollutant levels.

The material balance calculations to determine pollutant levels and manually recorded data for this test are presented in Appendix D.

4 Summary

4.1 Fuel Flow Measurements

It is apparent from Table 7 (see highlighted readings) that there were fuel savings associated with having the ESP-1000 engine speed pilot engaged - particularly at the two highest speed levels. The values for these short term tests were on the order of 5-6%. It should be noted that these measurements were based on manual readings taken over only a few hours for each tug and barge configuration tested. Approximately, a half hour was spent at each test rpm before moving to the next one. The Stellar Marine representative indicated that longer voyages are generally needed with the speed pilot engaged to realize a fuel savings (with repeatable results).

Table 7 Summary of Fuel Flow Data

Engine	rpm	Free Tug (pilot off) Fuel (gal/hr)	Full Barge (pilot off) Fuel (gal/hr)	Full Barge (pilot on) Fuel (gal/hr)	Light Barge (pilot off) Fuel (gal/hr)	Light Barge (pilot on) Fuel (gal/hr)
stbd	742	10.9	12.6	12.6	11.9	11.9
stbd	942	17.5	21.5	21.5	19.9	19.9
stbd	1072	24.4	31.4	29.5	27.9	27.0
stbd	1178	34.0	44.9	41.9	38.9	36.6
port	742	10.7	12.3	12.3	11.6	11.5
port	942	17.1	21.5	21.2	19.2	19.2
port	1072	23.4	31.1	29.4	27.4	26.9
port	1178	32.8	44.9	44.3	39.0	36.7

4.2 Pollutant Measurements

Table 8 presents a summary table of average emission pollutant levels recorded by the emission analyzers for the different tug running configurations. It is apparent in Table 8 that there is significantly more NO emissions than NO_2. Generally, in a diesel engine exhaust, the NO represents about 90% of the gas mixture, the NO_2 about 10%, and N_20 is negligible. Measurements were also made when the tug was at idle. These data are presented in Table 9.

Table 8 Summary of Pollutant Levels Recorded by Emission Analyzers

		Free Tug (ENERAC-stbd/ECOM-port)			Light Barge (ENERAC-port/ECOM-stbd)			Full Barge (ENERAC-port/ECOM-stbd)		
Engine	rpm	COppm	NOppm	NO2ppm	COppm	NOppm	NO2ppm	COppm	NOppm	NO2ppm
stbd	742	73	513	98	76	627	31	78	808	26
stbd	942	60	666	105	89	745	22	81	883	19
stbd	1072	77	692	83	95	697	16	79	829	17
stbd	1178	111	647	71	106	688	17	92	807	15
port	742	82	534	24	63	678	124	67	754	133
port	942	61	719	26	63	803	111	69	815	96
port	1072	66	721	21	76	765	89	71	810	83
port	1178	113	663	22	87	751	79	87	770	75

Note that the engine speed pilot was disengaged for these data

Table 9 Pollutant Levels Recorded by Emission Analyzers for Tug at Idle

(ENERAC-port/ECOM-stbd)

Engine	speed	COppm	NOppm	NO_2ppm
stbd	0*	792	31	46
port	0*	755	15	53

*Srpm is 0 but Erpm was 545(port) and 525(stbd)

Using the calculation procedure developed by Dr. Bentz in Appendix A, NOx and CO emission levels in grams per kilowatt-hour were calculated for the different running conditions tested on the tug. The calculations are based on a stoichiometric material balance of incoming fuel and air with exhaust. Figure 2 and 3 present these results.

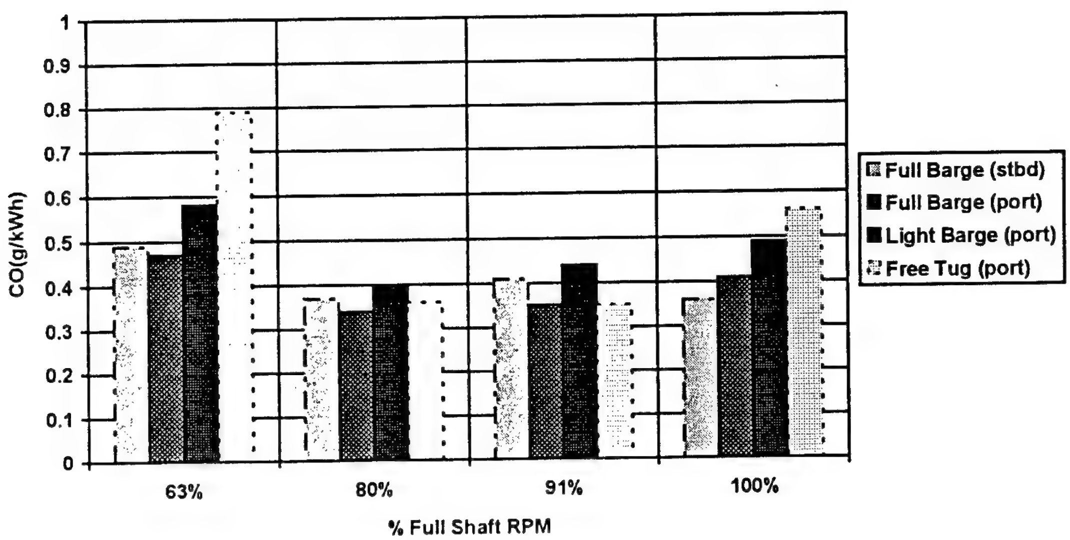


Figure 2 Tug COUGAR CO Emissions

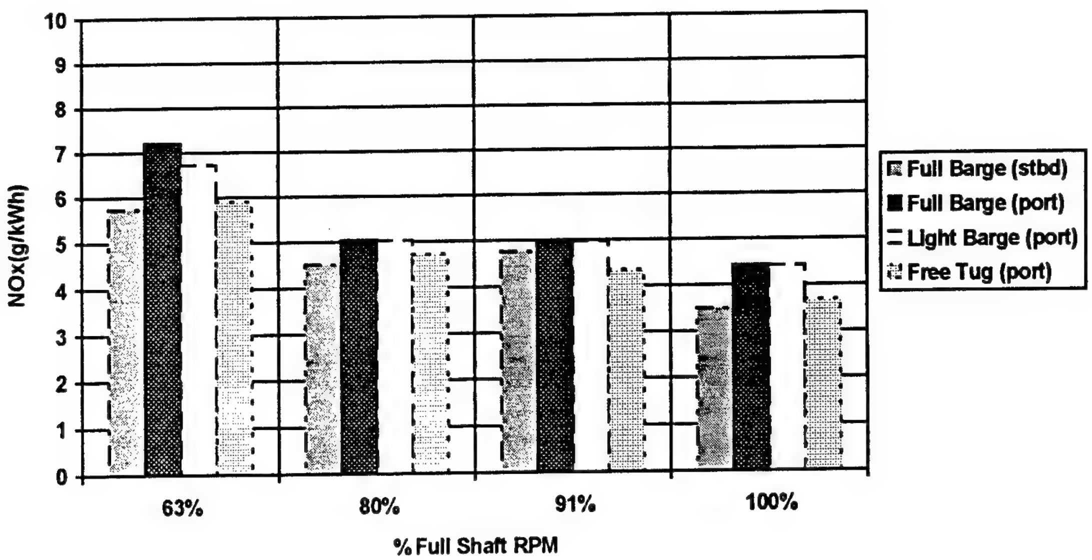


Figure 3 Tug COUGAR NOx Emissions

5 Conclusions

5.1 ISO 8178 Emission Factor

The International Maritime Organization (IMO) has developed proposed guidelines for controlling air pollution from ships. In these guidelines, the maximum NOx emissions at different rated engine speeds are recommended. The testing procedures used to develop engine NOx values are contained in the International Organization for Standardization (ISO) 8178, Parts 1, 4, and 5. Usually, these tests are done in the engine manufacturer's laboratory on test beds. The EPA issued a supplemental notice of proposed rule making which refines its November 1994 proposed rule. The EPA proposed an average NOx emission standard of 9.2 g/kWh, while the IMO NOx emission standard varies from 9.8g/kWh to 17.0g/kWh depending on engine speed. EPA's proposed NOx emission standard is an average in which the engine can be either below or above, so long as the emissions above the standard are compensated with the emissions below the standard. Whereas, the IMO NOx emission standard is a cap type standard that all engines must be less than.

ISO 8178 provides that each vessels emission be evaluated by a single statistic which takes into account a generic operating profile. Table 10 presents the weighted results for the free tug, tug pushing a full barge, and tug towing a light barge. The average weighted NOx values for each configuration are:

Free Tug	→ 4.5 g/kWh (port engine)
Tug w/ light barge	→ 5.1 g/kWh (port engine)
Tug w/ full barge	→ 4.9 g/kWh (port & stbd engine average)

These NOx values are below the IMO maximum allowable level of 10.85 g/kWh for a 1225 RPM rated engine. They are also well below the EPA average criteria of 9.2 g/kWh. This is illustrated in Figure 4.

Table 10 ISO 8178 NOx Factor (based on % full RPM when pulling a light barge and w/o the ESP-1000 Speed Pilot engaged)

		Free Tug			Light Barge			Full Barge		
Engine	RPM(b)	NOx (g/kWh)	Weight Factor	Weight NOx	NOx (g/kWh)	Weight Factor	Weight NOx	NOx (g/kWh)	Weight Factor	Weight NOx
stbd	63%	(a)	0.15	(a)	(a)	0.15	(a)	5.74	0.15	0.86
stbd	80%	(a)	0.15	(a)	(a)	0.15	(a)	4.52	0.15	0.68
stbd	91%	(a)	0.50	(a)	(a)	0.50	(a)	4.76	0.50	2.38
stbd	100%	(a)	0.20	(a)	(a)	0.20	(a)	3.49	0.20	0.70
	totals=			(a)			(a)			4.62
port	63%	5.90	0.15	0.89	6.71	0.15	1.01	7.21	0.15	1.08
port	80%	4.73	0.15	0.71	5.04	0.15	0.76	5.05	0.15	0.76
port	91%	4.34	0.50	2.17	4.98	0.50	2.49	5.01	0.50	2.51
port	100%	3.68	0.20	0.74	4.41	0.20	0.88	4.43	0.20	0.89
	totals=			4.50			5.13			5.23

(a) questionable measurements due to erratic turbocharger air flow readings

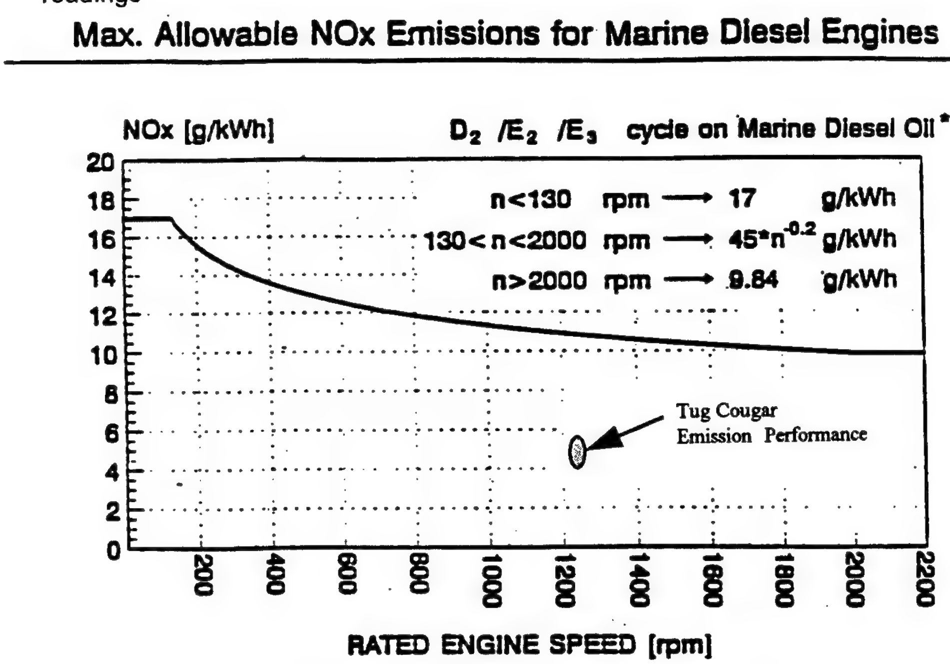


Figure 4 IMO NOx Emission Levels

5.2 NOx Interpretation

Presently, the IMO criteria requires that all NOx be reported as NO_2. The definition of NOx is that it is the sum of the nitrogen oxides which includes NO, NO_2, and N_2O. The molecular weight of NO is 30 whereas the molecular weight of NO_2 is 46. Reporting NO as NO_2 can have the effect of raising the determined value depending on the percent of NO present. For example, assuming that the exhaust mixture is about 90% NO, the weighted molecular weight is,

$$(30*0.9)+(46*0.1) = 31.6$$

The average weighted NOx factor for the full barge running configuration was determined to be 4.9 g/kWh. This value is based on a direct summation of NO and NO_2 recorded tug emissions. The total moles normalized by power can be approximated by,

$$\frac{4.9 \text{ g/kWh}}{31.6 \text{ g/mole}} = 0.156 \text{ moles NOx/kW-hr},$$

$$0.156 * 0.9 = 0.1404 \text{ moles NO}$$
$$0.156 * 0.1 = \underline{0.0156} \text{ moles } NO_2$$
$$\text{tot moles} \quad 0.156$$

Applying the interpretation of the IMO definition where NO is computed as NO_2 using a molecular weight of 46 results in,

$$0.156*46 = 7.2 \text{g/kWh}$$

This value still remains under the IMO criteria, but illustrates the disparity in calculated emission approaches. A rigorous application of reporting the NO as NO_2 would require a weighting factor application to the calculations in Appendix A. This was not done.

5.3 Portable Emission Testing Lessons Learned

It took a week of elapsed time aboard the Tug COUGAR to conduct two days worth of testing. This was because of the necessity of working around the boat's commercial schedule. One day was needed for the installation, i.e., approximately 12 hours of not being underway, for the strain gauge horsepower meters, and EMS-1000, and ESP-1000. Two consecutive days of testing would have allowed for plenty of time to carry out all the testing objectives. However, a week was spent aboard to capture the two days of testing needed because commercial operations of the tug, which often included anchoring offshore waiting for terminal availability, was not conducive to collecting emissions data on a continuous basis. Future shipboard emission testing aboard commercial vessels may require tradeoffs to minimize the potential impact on its commercial operations and the time spent aboard by test personnel including (1) a more efficient installation procedure to minimize vessel down time and (2) a reduction in the number of test runs conducted through statistical design of the experiments.

Air Flow Measurements

The Shortridge Flowhoods have been used on several shipboard emission tests without any difficulties. Unfortunately, in this test, the starboard flowmeter was not working properly for some of the test configurations. This prevented the development of average weighted values of NOx between the two engines for the free tug and light barge test runs.

A couple of mechanical failures of parts on the Flowhoods gave reason for concern. First a roll pin that holds the arms (vanes) in place for operation with the manual movement switch became loose and fell out. This was replaced during testing and a dab of epoxy was placed on the ends to prevent it from falling out. A second failure was when the bottom plastic vane broke off. This was epoxyed back on. In both cases, a small part (one metal and one plastic) could have been sucked into the turbocharger and caused damage to the engine. The flowhoods used in these applications need to be more robust in design. If the Coast Guard R&D Center uses these types of Flowhoods in the future, it will install fitted screens to their intakes to protect the turbocharger.

Readings were made from the flowhoods manually. In future shipboard emission tests it would be desirable to automate this data collection in conjunction with emission and ship power measurements.

Horsepower Measurements

The EMS-1000 data logging software, which recorded both shaft horsepower from the strain gage measurements and engine horsepower determined with the EMS-1000 system, was used to construct an overlay of horsepower measurements at various times during testing. These plots demonstrated close tracking between the two measurements. However, a scale difference exists between them. This difference has not been resolved, but appears to have been a problem with the strain gauge calibration settings.

The Stellar Marine EMS-1000 system has potential in saving setup time in dealing with horsepower measurements on main diesel engines. Additional testing is warranted to assess this as a replacement over traditional methods of instrumenting for power measurements.

Emission Analyzers

Table 11 presents a comparison of average recorded emission readings from both emission analyzers on one engine and then swapped to the other during the light barge testing. On average, the ECOM-KD exhibited 24% higher CO readings than the ENERAC Model 3000E. The accuracy of the ECOM-KD is 5% compared to 2% for readings of NO, NO_2, and CO on the ENERAC 3000E. Therefore, the disparity in the CO measurements cannot be explained by differences in the sensor's accuracy. It was determined after the test that the correct Precision Control Module (PCM) was not installed in the ENERAC 3000E. Unlike the single range sensors on the ECOM-KD, the ENERAC 3000E has PCMs for

CO, NO, and SO2 with selective range settings. Selection of the appropriate modules sets the measurement range of the instrument. There are PCMs with a low, mid, and high range settings. The ENERAC 3000E had a mid-range PCM (500-1000 ppm) installed. As it turned out, CO readings on the COUGAR were on the order of 100 ppm or less which would have required the more sensitive low-range PCM (0-500 ppm). This module was not available during the test. The reduced CO level readings on the ENERAC 3000E may be due to the less sensitive mid-range module (having been installed).

The ENERAC Model 3000E recorded higher levels of NO_2 than the ECOM-KD. The NO readings recorded by the ENERAC Model 3000E were on average 4% higher than readings by the ECOM-KD. The difference in NO readings between the instruments may be explained by the fact that the NO sensor on the ENERAC Model 3000 is temperature controlled. A sensor temperature of below 25 degrees Celsius is maintained to limit measurement drift in accordance with EPA's Conditional Test Method (CTM-022). Holding the temperature below 30 degrees Celsius is a means of improving sensor accuracy and reliability.

Table 11 Emission Levels Recorded with Analyzers Exchanged Between Engines

Tug Pulling Light Barge Test Data

Analyzer	Engine	rpm	COppm	NOppm	NO_2ppm
ENERAC	stbd	742	64	683	123
ENERAC	port	742	63	678	124
ECOM	stbd	742	76	627	31
ECOM	port	742	84	722	37
ENERAC	stbd	942	70	803	101
ENERAC	port	942	63	803	111
ECOM	stbd	942	89	745	22
ECOM	port	942	83	841	25
ENERAC	stbd	1072	80	814	78
ENERAC	port	1072	76	765	89
ECOM	stbd	1072	95	697	16
ECOM	port	1072	87	786	19
ENERAC	stbd	1178	82	788	69
ENERAC	port	1178	87	751	79
ECOM	stbd	1178	106	688	17
ECOM	port	1178	103	766	16

5.4 <u>ESP-1000 Speed Pilot</u>

An indication of fuel savings was measured when the engine speed pilot was engaged. The averaged manual readings in Table 6 demonstrated that most of the fuel savings occurred above 1000 rpm. The EMS-1000 data logging software provides a convenient tool to review data collected with and without the ESP-1000 engaged. On 13 May 1996, the tug was tested with a light (empty) barge being pulled behind it. The engine speed pilot was on for 2.7 hours and off for 9.0 hours. The gallons per mile were averaged with the results of 5.8 gal/mi when the engine speed pilot was engaged versus 8.2 gal/mi when the engine speed pilot was not used. This represents a savings of 2.4 gal/mi (or 29.3%). This is illustrated in Figure 5. Figure 5 presents a 12 hour running picture of the tug on 13 May 1996. Starboard and port rpm, GPS recorded speed, and port engine fuel consumption are plotted. The area of the rpm readings with the sawtooth appearance represent when emission testing was taking place at different rpm settings.

Although, an indication of fuel savings was apparent, further testing is needed. The Coast Guard R&D Center will conduct another emissions test on a Coast Guard WLIC construction tender in the fall of 1996. This emission test will include the use of the ESP-1000 and a specific test designed to comparatively quantify fuel savings.

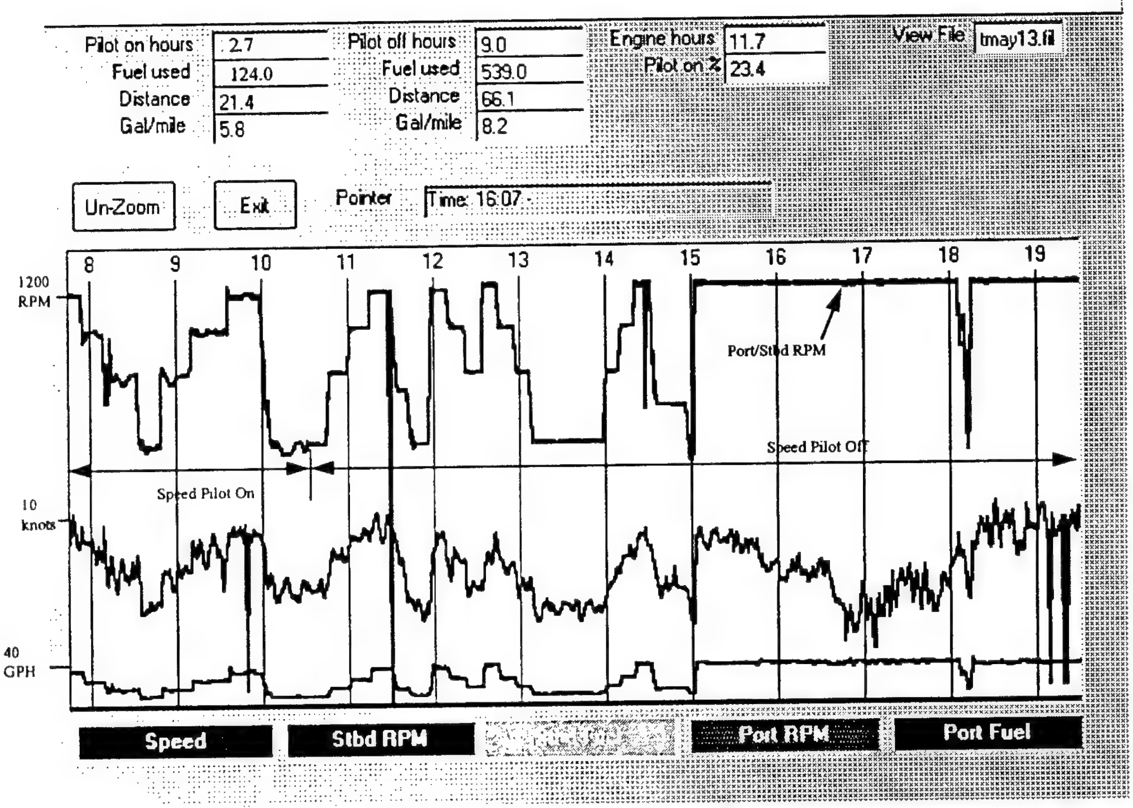


Figure 5 EMS-1000 Plot for Tug Pulling Light Barge Run

6 References

[1] Marine Exhaust Emissions Measurement of the M/V Kings Pointer, S.J. Allen, A.P. Bentz, U.S. Coast Guard Research & Development Center Report.

[2] ISO 8178, Part 4: Test Cycles for Different Engine Applications (1992), Section 6.5, Test Cycles Type E, "Marine Applications."

[3] Experimental Design on Marine Exhaust Emissions, M.J. Goodwin, Report No. CG-D-08-95, January 1995, U.S. Coast Guard Research and Development Center, NTIS Accession No. AD-A2936603.

[4] Shipboard Marine Engines Emissions Testing for the United States Coast Guard Headquarters, Delivery Order 31, Final Report, 1995, Environmental Transportation Consultants.

[5] Air Data Multimeter ADM-870 Electronic Microanometer, Technical Manual, Shortridge Instruments, Inc. Scottsdale, AZ.

[6] Technical Manual, Description, Operation, Installation and Maintenance Instruction for Propulsion Shaft Horsepower Measurement Systems, Model Series 1642A, Accurex Corp., Autodata Division (now Wireless Data Corporation), Mountain View CA.

[7] ECOM-KD Manual, Technical Manual, ECOM AMERICA, 3075 Breckinridge Blvd., Suite 420, Duluth, GA 30136.

[8] ENERAC 3000E Compliance-Level Emission Analyzers Instruction Manual, Energy Efficiency Systems, Inc., 1300 Shanes Drive, Westbury, NY 11590

[9] EMS-1000 Fuel Management System Manual, Stellar Marine.

[10] EPA's Conditional Test Method (CT-022), A scientifically Sound Framework for the Use of NOx Electrochemical Sensors, March 199, unpublished, Energy Efficiency Systems, Inc.

Appendix A
EXAMPLE EMISSION CALCULATION

[BLANK]

Calculations are based on a stoichiometric material balance of incoming fuel and air with exhaust. The basic assumption is that there is more than sufficient oxygen available in the air entering the diesel engine to effect complete combustion of the fuel components.

For the material balance, the quantity of air per unit time (including water vapor), and the quantity of fuel per unit time account for all incoming materials.

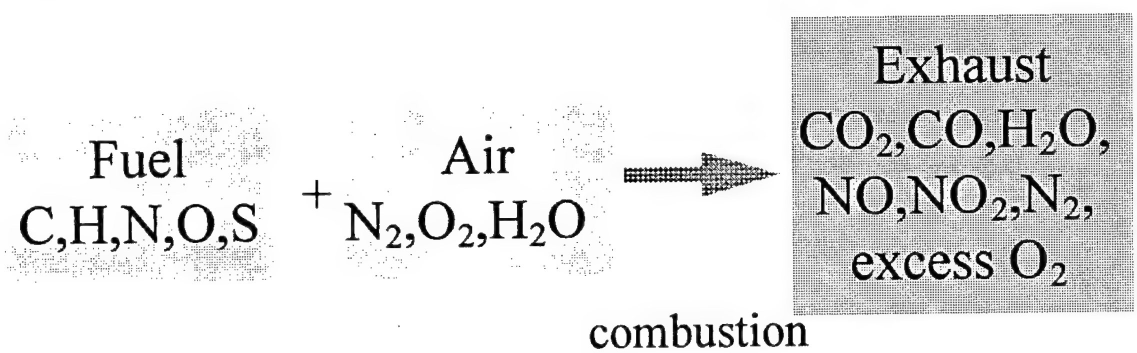
Laboratory analysis of the fuel quantitatively measures the elemental components of the fuel. Theoretical amounts of combustion products (assuming complete combustion) are computed using the equations below:

$$C + O_2 = CO_2 \qquad S + O_2 = SO_2$$
$$4H + O_2 = 2H_2O \qquad N + O_2 = NO_2$$

These equations permit calculation of the theoretical amount of oxygen required (and therefore air) for complete combustion. Any air above that amount is "excess air." In actuality, complete stoichiometric combustion does not occur. Thus, not all carbon is completely converted to CO_2. However, once the CO is experimentally determined, the actual CO_2 can be calculated. Similarly, not all nitrogen goes to NO_2, but the NO formed is independently measured.

Water is the product of combustion of hydrogen, but there is also water in the exhaust that entered as water vapor in the air. This source of water requires no additional oxygen, but must be accounted for in the total material balance. Any oxygen in the fuel (as oxygen-containing compounds) must be subtracted from the total oxygen required, since it contributes to the oxygen available.

Sulfur in the fuel produces SO_2, but the Tug COUGAR fuel gave levels below the sensor detection limits - thus no SO_2 was measurable, despite the presence of some sulfur in the fuel. Overall, the material balance is given schematically as follows:



By tracking the substances and their amounts, it is possible to compute the amounts expected in the exhaust of primary combustion products. Analysis of the exhaust for CO, NO, NO_2, and SO_2, permits complete material balance.

Table A1 presents the fuel analysis in the first two columns. The fuel analysis of samples of the Tug COUGAR's fuel was performed by Saybolt, Inc. Using the equations described previously, with the appropriate atomic weights, the moles of oxygen needed can be calculated.

Table A1
Calculated Oxygen Requirement for Complete Combustion Based on Fuel Analysis

Fuel Comp	lb/100lb fuel[a]	MWT of Comp	Moles of Comp	Moles 02 req
C	86.860	12.011	7.232	7.232
H	12.970	1.008	12.867	3.217[b]
S	0.150	32.060	0.005	0.005
O	0.020	16.000	-0.001	-0.001
N	0.020	14.007	0.001	0.001
H20	0.000	18.016	0.000	0.000
Ash	0.001			
Total	100.021			10.453

[a] based on fuel analysis
[b] represents 6.170 moles of water

From the information above, the temperature, pressure, and humidity of the incoming air, the goal is to calculate the moles of dry flue gas (DFG) generated per unit time. Although, the exiting gas is wet, the instruments used for measuring the combustion products must first dry the air to protect the electrochemical sensors. Thus, the concentration of NOx in ppm, for example, is based on the amount found in the DFG.

The following example calculations are performed for the data collected on the port Caterpillar engine when the tug was pushing a full barge without the EMS-1000 speed pilot engaged. The calculation is shown for a test rpm of 1072. Computations below are based on data taken on 15 May 1996 on the Tug COUGAR.

Density of Wet Air

$$\rho(\text{wet air})[\text{lb/ft}^3] = \frac{1.326 \times \text{Pres}}{459.6 + F} \qquad [1]$$

Air entering the engines had an average temperature of 85.4 deg F and measured an average atmospheric pressure of 30.6 in Hg, thus,

$$= \frac{1.326 \times 30.6}{459.6 + 85.4} = 0.0744 \text{ lb/ft}^3 \qquad [2]$$

Air Flow wet [lb/min]

= [2] x CFM(meas)
= 0.0744 lb/ft^3 x 1392 ft^3/min
= 103.63 lb/min [3]

Fuel Flow [gal/min]

= 31.08 GPH(meas) x 1 hr/60 min
= 0.518 gal/min [4]

Fuel Consumed [lb/min]

density of standard diesel approx. 7.09 lb/gal [5]
= 7.09 lb/gal(ρ_{diesel}) x [4]
= 3.67 lb/min [6]

Air / Fuel Ratio wet [lb/100lb]

= [3] / [6]
= 103.63 lb/min / 3.67 lb/min
= 2821 lb/100lb [7]

Air Flow dry [lb/min]

= Air Flow wet - (Air Flow wet x RHc),

where RHc is the humidity correction value from the pschrometric chart with measured temperature of 85.4 deg F (29.7 deg C) and measured averaged relative humidity of 17.3%,

= [3] - ([3] x 0.005)
= 103.63 lb/min - (103.63 lb/min x 0.005)
= 103.11 lb/min [8]

Air / Fuel Ratio dry [lb/100lb]

= [8] / [6]
= 103.11 lb/min / 3.67 lb/min
= 2807 lb/100lb [9]

The next step is to determine the total oxygen and nitrogen available for combustion in the incoming air, where the weight % of oxygen is 23.14% and that of nitrogen is 76.86%.

Total O_2 [lb O_2 / 100 lb Fuel]

$= [9] \times 0.2314$ lb O_2/lb air
$= 2807$ lb/100lb $\times 0.2314$ lb O_2/lb air
$= 650$ lb/100lb [10]

Total N_2 [lb N_2 / 100 lb Fuel]

$= [9] \times 0.7686$ lb O2/lb air
$= 2807$ lb/100lb $\times 0.7686$ lb O2/lb air
$= 2158$ lb/100lb [11]

Moles of O_2 Theoretically Required [moles O_2 / 100 lb Fuel]

$= 10.453$ moles/100lb [12]
(from fuel composition in Table A1)

Excess Air [lb air/100 lb fuel]

= Actual Air in - Theoretical Air In

$$= [9] - [12] \times \frac{32 \text{ lb } O_2}{1 \text{ mole } O_2} \times \frac{1 \text{ lb air}}{0.2314 \text{ lb } O_2}$$

$= 2807$ lb/100lb $- 1446$ lb/100lb
$= 1362$ lb/100lb [13]

Percent Excess Air [%]

= Excess Air / Theoretical Air in
$= 1362$ lb/100lb / 1446 lb/100lb $\times 100$
$= 94\%$ [14]

Excess O_2 [moles O_2/100lb Fuel]

$$= [13] \times \frac{0.2314 \text{ lb } O_2}{1 \text{ lb air}} \times \frac{1 \text{ mole } O_2}{32 \text{ lb } O_2}$$

$= 9.8$ moles/100lb [15]

Water in Air [moles H_2O/100 lb Fuel]

= [7] x lb H_2O/lb air (from Pschrometric Chart)

$$= 2821 \text{ lb air/100lb Fuel} \times 0.005 \text{ lb } H_2O\text{/lb air} \times \frac{1 \text{ mole } H_2O}{18 \text{ lb } H_2O}$$

$= 0.784$ moles H_2O/100lb [16]

$CO_2 + SO_2$ [moles (CO_2+SO_2) / 100lb Fuel]

$= 7.232 + 0.005$ (from Table A1)

$= 7.237$ moles/100lb [17]

O_2 Supplied [moles O_2/100lb Fuel]

$$= [10] \times \frac{1 \text{ mole } O_2}{32 \text{ lb } O_2}$$

$= 20.3$ moles/100lb [18]

N_2 Supplied [moles N_2/100lb Fuel]

$$= [11] \times \frac{1 \text{ mole } N_2}{28.161 \text{ lb } N_2}$$

$= 76.6$ moles/100lb [19]

H_2O Total [moles H_2O/100lb Fuel]

$$= [16] \times \frac{1\text{mole } H_2O}{18.016 \text{ lb } H_2O} + \text{combustion product}$$

(where the combustion product is from HCs and equal to 0.06434 moles H_2O/lb Fuel)

$= 0.784$ moles H_2O/100lb Fuel +
6.434 moles H_2O/100lb Fuel

$= 7.2$ moles/100lb [20]

or $= 129.6$ lb H_2O/100lb Fuel [21]

Total Moles of Wet Flue Gas [moles WFG/100lb Fuel]

$= (CO_2 + SO_2) + \text{excess } O_2 + N_2 + H_2O$

$= [17] + [15] + [19] + [20]$

$= 7.237$ moles/100lb + 9.8 moles/100lb + 76.6 moles/100lb + 7.2 moles/100lb

$= 100.8$ moles/100lb [22]

Total Moles of Dry Flue Gas [moles DFG/100lb Fuel]

= moles WFG - moles H_2O = [22] - [20]

= 100.8 moles/100lb - 7.2 moles/100lb

= 93.6 moles/100lb [23]

Moles CO [moles CO/100lb Fuel]

= COppm x [23]

= 71 x 10-6 x 93.6 moles/100lb

= 0.00664 moles/100lb [24]

Moles NO [moles NO/100lb Fuel]

$= NOppm \times [23]$
$= 810ppm \times 10\text{-}6 \times 93.6$ moles/100lb
$= 0.0758$ moles/100lb [25]

Moles NO_2 [moles NO_2/100lb Fuel]

$= NO_2ppm \times [23]$
$= 83 \times 10\text{-}6 \times 93.6$ moles/100lb
$= 0.0077$ moles/100lb [26]

Moles SO_2 [moles SO_2/100lb Fuel]

$= SO_2ppm \times [23]$
$= 0$ [27]

Moles CO_2 [moles CO_2/100lb Fuel]

= moles CO_2 (theoretical) - moles CO (actual [24])
$= 7.232 - 0.00664$
$= 7.225$ moles/100lb [28]

from CO_2 measurement on emission analyzer 8.5% CO_2
$= 0.085 \times [23]$
$= 0.085 \times 93.6$ moles/100lb
$= 7.956$ moles/100lb [28A]

Weight of NO [lb NO/100lb Fuel]

$= [25] \times 30.008$ lb NO/mole
$= 0.0758$ moles/100lb $\times 30.008$ lb NO/mole
$= 2.28$ lb/100lb [29]

Weight of NO_2 [lb NO2/100lb Fuel]

$= [26] \times 46.007$ lb NO_2/mole
$= 0.0077$ moles/100lb $\times 46.007$ lb NO_2/mole
$= 0.354$ lb/100lb [30]

Weight of SO_2 [lb SO_2/100lb Fuel]

$= 0$ [31]

Weight of CO_2 [lb CO2/100lb Fuel]

$= [28] \times 44.011$ lb CO_2/mole

$= 7.225$ moles/100lb x 44.011 lb CO_2/mole
$= 317.9$ lb/100lb [32]

NOx Weight [lb NOx/100lb Fuel]

= [29] + [30]
= 2.28 lb/100lb + 0.354 lb/100lb
= 2.634 lb/100lb [33]

Fuel Consumed in 1 hour [lb]

= [6] x 60 min/hr
= 3.67 lb/min x 60 min/hr
= 220.2 lb [34]

NOx Produced in 1 hour [grams NOx/hour]

= [33]/100 x [34]
= 2.634 lb/100lb /100 x 220.2 lb
= 5.80 lb NOx/hr
or = 5.80 lb NOx/hr x 453.4g/lb = 2629.7 g/hr [35]

Work done in 1 hour [kW-hr]

= shaft HP x 0.746 kW/HP
= 525.2 kW-hr [36]

NOx [g/kW-hr]

= [35] / [36]
= 2629.7 g/hr / 525.2 kW-hr
= 5.00 g/kW-hr [37]

(CO in g/kW-hr is calculated in the same fashion)

NOx [kg/ton of Fuel]

= [33] x 10
= 2.634 lb/100lb x 10
= 26.34 kg/ton of Fuel [38]

[BLANK]

Appendix B
Tug with Full Barge Emission Calculations

[B-3 through B-8 present the NOx calculations of the tug pushing the full barge without the engine speed pilot engaged;
B-9 through B-14 present the NOx calculations of the tug pushing the full barge with the engine speed pilot engaged;
B-15 presents the raw data sheet for the tug pushing the full barge without the engine speed pilot engaged;
B-16 presents the raw data sheet for the tug pushing the full barge with the engine speed pilot engaged;
B-17 through B-22 presents the NOx calculations of the tug at idle;
B-23 presents the raw data sheet for the tug at idle]

[BLANK]

Full Barge(pilot off;ECOM-stbd,ENERAC-port)				[4]				
Engine	Speed	HP	Fuel Flow	Fuel Flow	Air Flow	Air Temp	Air Temp	Air Press
	(rpm)	(ft lb)	(gal/hr)	(gal/min)	(CFM)	(deg F)	(deg C)	(in Hg)
stbd	742	212	12.63	0.211	533	89.7	32.1	30.8
stbd	942	467	21.50	0.358	864	91.9	33.3	30.8
stbd	1072	693	31.42	0.524	1421	87.1	30.6	30.8
stbd	1178	968	44.93	0.749	1515	85.7	29.9	30.8
port	742	217	12.30	0.205	605	87.8	31.0	30.6
port	942	478	21.53	0.359	931	86.9	30.5	30.6
port	1072	704	31.08	0.518	1392	85.4	29.7	30.6
port	1178	1010	44.85	0.748	1874	86.6	30.3	30.7

						[2]	[3]	[6]
RH	CO2	CO	NO	NO2	NOx	Air Wet	Air Wet	Fuel
(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(lb/cuft)	(lb/min)	(lb/min)
17.0	m	78	808	26	837	0.0744	39.60	1.49
17.0	m	81	883	19	901	0.0740	63.97	2.54
17.3	m	79	829	17	842	0.0747	106.18	3.71
17.2	m	92	807	15	823	0.0748	113.28	5.31
17.0	6.0	67	754	133	887	0.0741	44.82	1.45
17.0	8.1	69	815	96	912	0.0743	69.15	2.54
17.3	8.5	71	810	83	877	0.0744	103.63	3.67
17.2	8.6	87	770	75	849	0.0744	139.49	5.30

[7]		[8]	[9]	[10]	[11]	[12]	[13]	[14]
Air/Fuel Wet	RHc	Air Dry	Air/Fuel Dry	O_2/Fuel	N_2/Fuel	O_2/Fuel	XS Air/Fuel	XS Air/Fuel
(lb/100lb)		(lb/min)	(lb/100lb)	(lb/100lb)	(lb/100lb)	(moles/100lb)	(lb/100lb)	(%)
2652.94	0.005	39.41	2640	611	2029	10.453	1194.1	82.60
2517.88	0.005	63.65	2505	580	1926	10.453	1059.7	73.31
2860.22	0.005	105.65	2846	659	2187	10.453	1400.3	96.87
2133.42	0.005	112.71	2123	491	1632	10.453	677.2	46.84
3083.54	0.005	44.59	3068	710	2358	10.453	1622.5	112.24
2717.77	0.005	68.81	2704	626	2078	10.453	1258.6	87.07
2821.36	0.005	103.11	2807	650	2158	10.453	1361.7	94.20
2631.96	0.005	138.79	2619	606	2013	10.453	1173.2	81.16

[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
XS O_2/Fuel	H20/Fuel	CO_2+SO_2/Fuel	O_2/Fuel	N_2/Fuel	H_2Otot/Fuel	H_2Otot/Fuel	WFGtot/Fuel	DFGto/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(moles/100lb)	(moles/100lb)
8.6	0.737	7.236	19.088	72.045	10.49	188.83	98.41	87.92
7.7	0.699	7.236	18.116	68.377	10.28	185.08	93.56	83.28
10.1	0.795	7.236	20.580	77.674	10.81	194.58	105.85	95.04
4.9	0.593	7.236	15.350	57.936	9.69	174.41	79.76	70.07
11.7	0.857	7.236	22.186	83.738	11.15	200.78	113.86	102.71
9.1	0.755	7.236	19.555	73.806	10.59	190.63	100.73	90.14
9.8	0.784	7.236	20.300	76.619	10.75	193.50	104.45	93.70
8.5	0.731	7.236	18.937	71.475	10.46	188.25	97.65	87.20

[24]	[25]	[26]	[27]	[28]	[28A]	[29]	[30]	[31]
CO	NO	NO2	SO_2	CO_2	CO_2	NO/Fuel	NO_2/Fuel	SO_2/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(lb/100lb)	(lb/100lb)
0.00689	0.07099	0.00229	0	7.225	m	2.130	0.105	0
0.00673	0.07351	0.00154	0	7.225	m	2.206	0.071	0
0.00752	0.07875	0.00157	0	7.224	m	2.363	0.072	0
0.00642	0.05656	0.00105	0	7.225	m	1.697	0.048	0
0.00692	0.07744	0.01363	0	7.225	6.197	2.324	0.627	0
0.00623	0.07347	0.00865	0	7.225	7.302	2.205	0.398	0
0.00662	0.07593	0.00775	0	7.225	7.996	2.278	0.356	0
0.00759	0.06713	0.00651	0	7.224	7.470	2.014	0.300	0

[32]	[33]	[34]	[35]	[36]	[37]	[38]
CO_2/Fuel	NOx/Fuel	fuel 1hr	NOx 1hr	Pwr	NOx out	NOx out
(lb/100lb)	(lb/100lb)	(lb)	(gal/hr)	(kW hr)	(g/kW-hr)	(kg/ton)
318.0	2.235	89.570	907.86	158.2	5.74	22
318.0	2.277	152.435	1573.47	348.4	4.52	23
317.9	2.435	222.744	2459.54	517.0	4.76	24
318.0	1.746	318.577	2521.31	722.1	3.49	17
318.0	2.951	87.207	1166.72	161.9	7.21	30
318.0	2.603	152.671	1801.64	356.6	5.05	26
318.0	2.635	220.381	2632.77	525.2	5.01	26
317.9	2.314	317.987	3336.00	753.5	4.43	23

Full Barge(pilot on;ECOM-stbd,ENERAC-port)				[4]				
Engine	Speed	HP	Fuel Flow	Fuel Flow	Air Flow	Air Temp	Air Temp	Air Press
	(rpm)	(ft lb)	(gal/hr)	(gal/min)	(CFM)	(deg F)	(deg C)	(in Hg)
stbd	742	203	12.57	0.209	519	88.1	31.2	30.8
stbd	942	452	21.53	0.359	871	88.2	31.2	30.8
stbd	1072	638	29.48	0.491	1303	89.9	32.2	30.8
stbd	1178	903	32.82	0.547	1681	88.8	31.6	30.8
port	742	213	12.27	0.204	608	84.2	29.0	30.6
port	942	478	21.22	0.354	916	84.5	29.2	30.6
port	1072	677	29.38	0.490	1302	84.7	29.3	30.6
port	1178	1020	44.27	0.738	1893	85.6	29.8	30.6

						[2]	[3]	[6]
RH	CO2	CO	NO	NO2	NOx	Air Wet	Air Wet	Fuel
(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(lb/cuft)	(lb/min)	(lb/min)
18.0	m	83	788	28	810	0.0746	38.67	1.48
18.5	m	83	844	21	863	0.0746	65.00	2.54
18.5	m	83	802	18	821	0.0744	96.95	3.48
18.5	m	93	781	15	798	0.0745	125.23	3.88
18.0	5.9	65	730	116	846	0.0746	45.37	1.45
18.5	7.9	76	791	91	883	0.0746	68.34	2.51
18.5	8.5	77	799	76	877	0.0746	97.15	3.47
18.5	8.6	82	767	72	840	0.0745	141.07	5.23

[7]		[8]	[9]	[10]	[11]	[12]	[13]	[14]
Air/Fuel Wet	RHc	Air Dry	Air/Fuel Dry	O_2/Fuel	N_2/Fuel	O_2/Fuel	XS Air/Fuel	XS Air/Fuel
(lb/100lb)		(lb/min)	(lb/100lb)	(lb/100lb)	(lb/100lb)	(moles/100lb)	(lb/100lb)	(%)
2604.34	0.005	38.48	2591	600	1992	10.453	1145.7	79.26
2554.38	0.005	64.67	2542	588	1953	10.453	1096.0	75.82
2782.80	0.005	96.47	2769	641	2128	10.453	1323.3	91.54
3229.32	0.005	124.60	3213	744	2470	10.453	1767.6	122.28
3129.74	0.005	45.14	3114	721	2393	10.453	1668.5	115.42
2725.96	0.005	68.00	2712	628	2085	10.453	1266.8	87.63
2797.88	0.005	96.66	2784	644	2140	10.453	1338.3	92.58
2696.89	0.005	140.36	2683	621	2062	10.453	1237.8	85.63

[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
XS O_2/Fuel	H20/Fuel	CO_2+SO_2/Fuel	O_2/Fuel	N_2/Fuel	H_2Otot/Fuel	H_2Otot/Fuel	WFGtot/Fuel	DFGto/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(moles/100lb)	(moles/100lb)
8.3	0.723	7.236	18.738	70.725	10.42	187.48	96.66	86.25
7.9	0.710	7.236	18.379	69.368	10.34	186.09	94.87	84.53
9.6	0.773	7.236	20.023	75.571	10.69	192.43	103.07	92.38
12.8	0.897	7.236	23.235	87.697	11.38	204.82	119.09	107.72
12.1	0.869	7.236	22.519	84.993	11.23	202.06	115.52	104.29
9.2	0.757	7.236	19.614	74.028	10.60	190.85	101.03	90.42
9.7	0.777	7.236	20.131	75.981	10.71	192.85	103.61	92.90
9.0	0.749	7.236	19.404	73.238	10.56	190.05	99.98	89.43

[24]	[25]	[26]	[27]	[28]	[28A]	[29]	[30]	[31]
CO	NO	NO2	SO_2	CO_2	CO_2	NO/Fuel	NO_2/Fuel	SO_2/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(lb/100lb)	(lb/100lb)
0.00719	0.06793	0.00239	0	7.225	m	2.039	0.110	0
0.00697	0.07134	0.00178	0	7.225	m	2.141	0.082	0
0.00770	0.07407	0.00165	0	7.224	m	2.223	0.076	0
0.00996	0.08413	0.00163	0	7.222	m	2.524	0.075	0
0.00678	0.07610	0.01210	0	7.225	6.119	2.284	0.557	0
0.00689	0.07153	0.00826	0	7.225	7.159	2.146	0.380	0
0.00711	0.07425	0.00709	0	7.225	7.850	2.228	0.326	0
0.00736	0.06860	0.00639	0	7.224	7.646	2.059	0.294	0

[32]	[33]	[34]	[35]	[36]	[37]	[38]
CO_2/Fuel	NOx/Fuel	fuel 1hr	NOx 1hr	Pwr	NOx out	Nox out
(lb/100lb)	(lb/100lb)	(lb)	(gal/hr)	(kW hr)	(g/kW-hr)	(kg/ton)
318.0	2.148	89.098	867.860	151.4	5.73	21
318.0	2.223	152.671	1538.473	336.9	4.57	22
317.9	2.299	209.037	2178.469	475.8	4.58	23
317.8	2.600	232.670	2742.398	673.3	4.07	26
318.0	2.840	86.971	1119.972	158.6	7.06	28
318.0	2.526	150.426	1723.021	356.8	4.83	25
318.0	2.554	208.328	2412.828	504.8	4.78	26
318.0	2.353	313.851	3348.108	761.2	4.40	24

Tug Cougar Pushing Full Barge (speed pilot off)																					
Run Seq	Pilot/Eng	Date/Time	O2%	COppm	CO2ppm	NOppm	NO2ppm	NOxppm	SO2ppm	STemp	CFM	Fdeg	Hg"	RH%	CGHP	CGTQ	CGRPM	STgal/Hr	STRPM	STHP	GPSsp
E1.80	off/stbd	5-15/1121	10.7	85	-	861	20	885	0	621	472	90.7	30.8	17	494	132	191	21.1	945	356	6.7
E2.80	off/stbd	5-15/1122	10.7	85	-	860	20	879	0	621	459	91.2	30.8	17	465	128	191	21.1	944	352	6.2
E3.80	off/stbd	5-15/1123	10.7	90	-	867	20	881	0	621	413	90.1	30.7	17	462	128	191	21.9	945	348	6.7
E1.80	off/port	5-15/1120	10.2	63	8.1	800	86	887	-	597	483	87.2	30.6	17	495	143	191	22.8	942	346	6.7
E2.80	off/port	5-15/1121	10.1	64	8.1	793	93	887	-	601	464	85.8	30.6	17	487	141	191	21.5	942	340	6.2
E3.80	off/port	5-15/1122	10.1	66	8.1	794	94	888	-	601	468	86.7	30.6	17	481	139	191	21.3	948	340	6.7
E1.91	off/stbd	5-15/1127	10.2	75	-	778	19	788	0	687	726	88.3	30.8	18	700	170	217	31.8	1073	552	7
E2.91	off/stbd	5-15/1128	10.2	85	-	786	17	803	0	687	749	87.9	30.8	18	686	167	217	31.5	1073	540	7.6
E3.91	off/stbd	5-15/1129	10.2	85	-	794	16	810	0	687	646	88.1	31.1	18	689	168	217	31.6	1073	546	7.4
E1.91	off/port	5-15/1131	9.7	68	8.5	788	75	864	-	664	729	86.3	30.6	18	732	183	217	31.8	1071	546	7
E2.91	off/port	5-15/1132	9.7	70	8.4	791	75	866	-	664	739	86.7	30.6	18	723	180	217	30.9	1073	540	7.6
E3.91	off/port	5-15/1133	9.7	73	8.4	787	75	862	-	666	703	86.2	30.6	18	730	181	217	31.2	1073	534	7.4
E1.100	off/stbd	5-15/1136	10.1	85	-	769	15	784	0	720	665	87.4	30.8	18	979	214	240	45.8	1189	814	8.7
E2.100	off/stbd	5-15/1137	10.1	100	-	785	14	797	0	720	584	86.6	30.8	18	962	211	240	44.6	1188	782	7.6
E3.100	off/stbd	5-15/1138	10.1	100	-	790	14	806	0	722	609	86.7	30.8	18	960	210	240	44.3	1188	796	8.8
E1.100	off/port	5-15/1141	9.7	81	8.4	747	61	809	-	687	996	85.9	30.7	18	1034	229	241	45.6	1192	816	8.7
E2.100	off/port	5-15/1142	9.6	86	8.5	757	69	826	-	691	929	95.9	30.7	18	1003	223	241	44.7	1092	802	7.6
E3.100	off/port	5-15/1143	9.5	87	8.6	762	70	833	-	694	899	86.8	30.7	18	1026	226	241	45	1191	810	8.7
F1.100	off/stbd	5-15/0946	10	80	-	819	17	840	0	730	887	84.3	30.7	17	980	215	240	45.2	1190	808	7.7
F2.100	off/stbd	5-15/0947	10	90	-	834	15	853	0	730	873	84.5	30.7	15	973	214	240	45.2	1189	808	9
F3.100	off/stbd	5-15/0948	9.9	95	-	846	15	860	0	732	927	84.9	30.7	17	954	206	241	44.5	1189	806	8.6
F1.100	off/port	5-15/0949	9.6	87	8.5	793	76	870	-	722	879	83.5	30.6	17	1005	223	241	44.6	1192	802	7.7
F2.100	off/port	5-15/0950	9.4	91	8.7	773	85	878	-	726	940	83.4	30.6	15	1000	223	241	44.6	1191	808	9
F3.100	off/port	5-15/0951	9.3	90	8.7	787	87	875	-	727	978	84.2	30.6	17	994	222	241	44.6	1190	802	8.6
F1.91	off/stbd	5-15/0956	10	70	-	867	16	876	0	702	653	85.1	30.7	17	680	165	217	30.7	1074	524	7.9
F2.91	off/stbd	5-15/0957	10	80	-	869	16	882	0	702	749	85.7	30.7	15	707	172	217	31.1	1076	548	8
F3.91	off/stbd	5-15/0958	9.9	80	-	878	15	891	0	705	741	87.4	30.7	18	698	169	217	31.8	1075	552	7
F1.91	off/port	5-15/0959	9.5	69	8.6	837	91	828	-	694	633	83.4	30.6	17	695	174	217	30.4	1074	524	7.9
F2.91	off/port	5-15/1000	9.4	71	8.7	825	91	916	-	697	677	83.6	30.6	15	722	181	217	30.7	1074	524	8
F3.91	off/port	5-15/1001	9.4	73	8.6	834	89	924	-	692	695	86.4	30.6	18	623	180	217	31.5	1073	546	7
F1.80	off/stbd	5-15/1057	10.7	65	-	895	17	911	0	642	351	90.6	30.8	17	454	126	190	21.3	943	340	6.6
F2.80	off/stbd	5-15/1058	10.7	80	-	908	17	925	0	640	419	98.7	30.8	17	463	128	190	21.8	941	350	6
F3.80	off/stbd	5-15/1059	10.6	80	-	905	17	925	0	639	479	90.3	30.8	17	465	129	190	21.8	942	352	6.9
F1.80	off/port	5-15/1101	10.2	75	8.1	844	99	943	-	619	477	88	30.6	17	458	134	189	21.2	949	348	6.6
F2.80	off/port	5-15/1102	10.1	74	8.1	837	102	939	-	621	464	86.7	30.6	17	473	136	190	21.2	936	334	6
F3.80	off/port	5-15/1103	10.1	73	8.1	822	102	925	-	621	438	86.7	30.6	17	476	139	190	21.2	936	328	6.9
F1.63	off/stbd	5-15/1108	13.5	70	-	797	25	821	0	473	238	90.8	30.8	17	208	73	151	12.6	744	160	5.6
F2.63	off/stbd	5-15/1109	13.4	80	-	808	26	838	0	472	286	90.3	30.8	17	214	75	151	12.7	744	164	5
F3.63	off/stbd	5-15/1110	13.3	85	-	817	27	852	0	471	275	88	30.8	17	214	75	151	12.6	744	160	5
F1.63	off/port	5-15/1112	13	66	6	753	131	884	-	464	308	88.8	30.6	17	212	83	150	12.1	743	152	5.6
F2.63	off/port	5-15/1113	12.9	68	6	751	133	884	-	459	306	87.2	30.6	17	218	85	151	12.3	743	160	5
F3.63	off/port	5-15/1114	12.9	68	6.1	758	134	893	-	458	293	87.5	30.6	17	220	85	151	12.5	743	156	5

Tug Cougar Pushing Full Barge (speed pilot on)																					
Run Seq	Pilot/Eng	Date/Time	O2%	COppm	CO2ppm	NOppm	NO2ppm	NOxppm	SO2ppm	STemp	CFM	Fdeg	Hg"	RH%	CGHP	CGTQ	CGRPM	STgal/Hr	STRPM	STHP	GPSsp
H1.100	on/stbd	5-15/1207	10	80	-	807	13	820	0	728	775	87.5	30.8	18	890	199	236	41.2	1164	734	8.5
H2.100	on/stbd	5-15/1208	10	90	-	814	13	832	0	726	901	87.2	30.8	18	895	200	236	14.5	1165	736	7.7
H3.100	on/stbd	5-15/1209	10	90	-	814	12	826	0	726	842	89.6	30.8	18	897	200	236	14.5	1066	734	8.7
H1.100	on/port	5-15/1211	9.5	84	8.6	788	74	863	-	694	919	86.9	30.6	18	1013	226	240	44.6	1190	800	8.5
H2.100	on/port	5-15/1212	9.5	80	8.6	786	75	862	-	695	867	86.3	30.6	18	1017	227	241	43.2	1189	800	7.7
H3.100	on/port	5-15/1213	9.5	82	8.6	783	74	858	-	696	987	87.1	30.6	18	1009	225	241	44.8	1179	724	8.7
H1.91	on/stbd	5-15/1219	10.1	70	-	832	14	846	0	697	635	90.6	30.9	18	652	161	214	30.3	1061	516	7.6
H2.91	on/stbd	5-15/1220	10	75	-	836	14	843	0	700	564	91.9	30.8	18	684	167	216	30.6	1070	528	8.4
H3.91	on/stbd	5-15/1221	10	80	-	829	13	844	0	701	697	91.9	30.8	18	629	166	216	30.8	1069	522	8.3
H1.91	on/port	5-15/1223	9.5	72	8.6	805	77	883	-	669	648	84.6	30.6	18	690	174	215	30.1	1062	518	7.6
H2.91	on/port	5-15/1224	9.5	72	8.6	809	77	887	-	676	663	85	30.6	18	712	175	216	30.5	1066	514	8.4
H3.91	on/port	5-15/1225	9.5	72	8.6	800	77	878	-	676	643	85.6	30.6	18	707	177	216	31.2	1072	528	8.3
H1.80	on/stbd	5-15/1230	10.8	70	-	861	19	876	0	635	382	90.9	30.9	18	450	125	190	21.3	944	342	6.7
H2.80	on/stbd	5-15/1231	10.6	80	-	866	19	875	0	637	397	89.4	30.8	18	454	126	191	21.8	943	342	7
H3.80	on/stbd	5-15/1232	10.6	85	-	860	19	877	0	636	376	86.1	30.8	18	442	124	189	21.1	933	338	6.9
H1.80	on/port	5-15/1233	10.3	76	8	795	96	892	-	604	468	84.2	30.6	18	481	135	192	21.4	947	338	6.7
H2.80	on/port	5-15/1234	10.3	79	8	801	96	898	-	607	445	84	30.6	18	466	136	190	21	938	328	7
H3.80	on/port	5-15/1235	10.3	77	8	791	96	887	-	607	471	87.3	30.6	18	469	137	190	20.9	938	328	6.9
H1.63	on/stbd	5-15/1239	13.6	80	-	788	26	794	0	465	250	88.8	30.8	18	197	70	151	12.6	749	162	6.4
H2.63	on/stbd	5-15/1240	13.5	85	-	786	28	814	0	466	264	89.2	30.8	18	213	74	152	12.9	751	164	6.1
H3.63	on/stbd	5-15/1241	13.4	85	-	789	29	821	0	466	264	86.4	30.8	18	199	71	149	12.2	754	154	5.6
H1.63	on/port	5-15/1244	13.1	62	5.9	733	111	844	-	433	302	84.6	30.6	18	206	81	151	12.4	749	158	6.4
H2.63	on/port	5-15/1245	13.1	65	5.9	732	118	851	-	444	310	84.3	30.6	18	221	86	152	12.5	749	152	6.1
H3.63	on/port	5-15/1246	13.2	68	5.8	724	119	844	-	439	300	83.7	30.6	18	211	83	150	11.9	732	150	5.6
G1.80	on/stbd	5-15/1259	10.9	80	-	813	23	838	0	623	551	90.3	30.8	19	457	126	192	21.2	946	342	7.1
G2.80	on/stbd	5-16/0100	10.8	90	-	829	23	851	0	622	437	85.8	30.8	19	451	125	191	21.9	945	348	6.7
G3.80	on/stbd	5-16/0101	10.8	90	-	835	23	858	0	620	471	86.7	30.8	19	456	126	191	21.9	946	348	8.3
G1.80	on/port	5-16/0102	10.5	75	7.8	787	80	868	-	566	451	83.8	30.7	19	484	135	192	21.1	946	338	7.1
G2.80	on/port	5-16/0103	10.5	75	7.8	784	88	872	-	576	434	83.9	30.6	19	482	135	192	21.5	949	344	6.7
G3.80	on/port	5-16/0104	10.5	75	7.9	788	92	880	-	582	479	84	30.6	19	488	140	192	21.4	946	338	8.3
G1.91	on/stbd	5-16/0107	10.4	80	-	765	23	785	0	672	656	90.1	30.9	19	614	155	210	28.3	1041	472	7.9
G2.91	on/stbd	5-16/0108	10.4	95	-	773	22	798	0	671	692	87.1	30.8	19	610	154	209	27.8	1035	468	7.8
G3.91	on/stbd	5-16/0109	10.4	100	-	776	21	807	0	672	665	87.7	30.8	19	638	159	211	29.1	1046	492	7.7
G1.91	on/port	5-16/0111	9.9	80	8.3	805	75	880	-	642	730	84	30.6	19	644	167	210	27.8	1037	470	7.9
G2.91	on/port	5-16/0112	9.9	81	8.3	794	76	871	-	643	654	85.4	30.7	19	654	165	210	27.8	1037	466	7.8
G3.91	on/port	5-16/0113	9.8	82	8.3	783	76	860	-	644	569	83.3	30.6	19	653	165	211	28.9	1037	494	7.7
G1.100	on/stbd	5-16/0117	10.2	95	-	737	19	759	0	712	906	89.7	30.9	19	910	202	237	42.3	1172	750	8.7
G2.100	on/stbd	5-16/0118	10.2	100	-	757	18	775	0	714	786	89.8	30.8	19	906	202	236	41.8	1171	746	8.9
G3.100	on/stbd	5-16/0119	10.2	100	-	757	16	775	0	714	832	89.1	30.8	19	917	204	237	42.6	1171	756	9.3
G1.100	on/port	5-16/0121	9.7	82	8.5	748	68	816	-	675	983	84.3	30.7	19	1026	227	240	44.2	1191	808	8.7
G2.100	on/port	5-16/0122	9.6	82	8.5	747	69	817	-	680	953	85.3	30.6	19	1057	223	240	44.7	1189	882	8.9
G3.100	on/port	5-16/0123	9.5	84	8.5	751	69	821	-	682	971	83.5	30.7	19	1000	223	240	44.1	1186	808	9.3

Tug at IDLE				[4]				
Engine	Speed	HP	Fuel Flow	Fuel Flow	Air Flow	Air Temp	Air Temp	Air Press
	(rpm)	(ft lb)	(gal/hr)	(gal/min)	(CFM)	(deg F)	(deg C)	(in Hg)
stbd	0(1)	0	4.77	0.079	239	87.4	30.8	30.8
port	0(1)	0	4.83	0.081	252	83.2	28.4	30.7
	(1)SRPM is 0 but Erpm is 545(port) and 525(stbd)							
	(2)Engine HP not measured							

						[2]	[3]	[6]
RH	CO2	CO	NO	NO_2	NOx	Air Wet	Air Wet	Fuel
(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(lb/cuft)	(lb/min)	(lb/min)
19.0	m	792	31	46	77	0.0747	17.86	0.56
19.0	1.3	759	15	53	67	0.0750	18.90	0.57

[7]		[8]	[9]	[10]	[11]	[12]	[13]	[14]
Air/Fuel Wet	RHc	Air Dry	Air/Fuel Dry	O_2/Fuel	N_2/Fuel	O_2/Fuel	XS Air/Fuel	XS Air/Fuel
(lb/100lb)		(lb/min)	(lb/100lb)	(lb/100lb)	(lb/100lb)	(moles/100lb)	(lb/100lb)	(%)
3171.50	0.005	17.77	3156	730	2425	10.453	1710.1	118.30
3309.23	0.005	18.81	3293	762	2531	10.453	1847.1	127.78

[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
XS O_2/Fuel	H20/Fuel	CO_2+SO_2/Fuel	O_2/Fuel	N_2/Fuel	H_2Otot/Fuel	H_2Otot/Fuel	WFGtot/Fuel	DFGto/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(moles/100lb)	(moles/100lb)
12.4	0.881	7.236	22.819	86.127	11.29	203.22	117.02	105.73
13.4	0.919	7.236	23.810	89.868	11.50	207.04	121.96	110.46

[24]	[25]	[26]	[27]	[28]	[28A]	[29]	[30]	[31]
CO	NO	NO2	SO_2	CO_2	CO_2	NO/Fuel	NO_2/Fuel	SO_2/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(lb/100lb)	(lb/100lb)
0.08370	0.00328	0.00486	0	7.148	m	0.098	0.224	0
0.08387	0.00162	0.00585	0	7.148	1.381	0.049	0.269	0

[32]	[33]	[34]	[35]	[36]	[37]	[38]
CO_2/Fuel	NOx/Fuel	fuel 1hr	NOx 1hr	Pwr	NOx out	Nox out
(lb/100lb)	(lb/100lb)	(lb)	(gal/hr)	(kW hr)	(g/kW-hr)	(kg/ton)
314.6	0.322	33.796	49.357	0(2)	*(2)	3.2
314.6	0.318	34.268	49.402	0(2)	*(2)	3.2

Tug Cougar - Idle Speed																					
Run Seq	Pilot/Eng	Date/Time	O2%	COppm	CO2ppm	NOppm	NO2ppm	NOxppm	SO2ppm	Stemp	CFM	Fdeg	Hg"	RH%	CGHP	CGTQ	CGRPM	STgal/Hr	STRPM	STHP	GPS
IDLE	off/stbd	5-16/0132	19.3	780	-	32	44	76	0	282	235	86.6	30.9	19	0	-32	0	4.7	525	0	0
IDLE	off/stbd	5-16/0133	19.3	795	-	31	46	77	0	275	251	89.1	30.8	19	0	-27	0	4.7	525	0	0
IDLE	off/stbd	5-16/0134	19.3	800	-	30	48	78	0	269	231	86.5	30.8	19	0	-25	0	4.9	526	0	0
IDLE	off/port	5-16/0136	19.3	699	1.2	18	50	69	-	338	236	83.3	30.7	19	0	25	0	4.9	545	0	0
IDLE	off/port	5-16/0137	19.3	758	1.2	15	52	68	-	351	246	83.9	30.7	19	0	21	0	4.8	545	0	0
IDLE	off/port	5-16/0138	19.3	780	1.3	11	54	66	-	347	274	82.3	30.7	19	0	20	0	4.8	545	0	0
IDLE	off/port	5-16/0139	19.3	800	1.3	9	56	65	-	337	-	-	-	-	-	-	-	-	-	-	-

[BLANK]

Appendix C
Tug with Light Barge Emission Calculations

[C-3 through C-8 present the NOx calculations of the tug towing the light barge without the engine speed pilot engaged and with the ECOM and ENERAC emission analyzers used on the stbd & port engines, respectively;
C-9 through C-14 present the NOx calculations of the tug towing the light barge without the engine speed pilot engaged and with the ECOM and ENERAC emission analyzers used on the port & stbd engines, respectively;
C-15 through C-19 present the NOx calculations of the tug towing the light barge with the engine speed pilot engaged;
C-20 presents the raw data sheet for the tug towing the light barge with the engine speed pilot engaged;
C-21 through C-22 present the raw data sheet for the tug towing the light barge without the engine speed pilot engaged]

[BLANK]

Light Barge(pilot off;ECOM-stbd, ENERAC-port)				[4]				
Engine	Speed	HP	Fuel Flow	Fuel Flow	Air Flow	Air Temp	Air Temp	Air Press
	(rpm)	(ft lb)	(gal/hr)	(gal/min)	(CFM)	(deg F)	(deg C)	(in Hg)
stbd	742	240	11.7	0.195	367	78.8	26.0	30.5
stbd	942	481	20.0	0.334	447	80.5	26.9	30.5
stbd	1072	685	27.9	0.464	628	79.6	26.4	30.5
stbd	1178	911	38.6	0.644	845	80.9	27.2	30.5
port	742	221	11.5	0.191	628	78.4	25.8	30.2
port	942	452	19.0	0.317	867	80.6	27.0	30.3
port	1072	673	27.4	0.456	1376	81.4	27.4	30.3
port	1178	896	37.8	0.630	1681	80.6	27.0	30.2
(m) CO2 data were not collected on the stbd engine								
(n) stbd air flow readings were eratic during test								

						[2]	[3]	[6]
RH	CO2	CO	NO	NO_2	NOx	Air Wet	Air Wet	Fuel
(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(lb/cuft)	(lb/min)	(lb/min)
21.0	m	76	627	31	656	0.0751	27.55	1.38
20.5	m	89	745	22	769	0.0748	33.46	2.37
21.0	m	95	697	16	713	0.0749	47.03	3.29
20.4	m	106	688	17	707	0.0749	63.26	4.57
21.0	5.1	63	678	124	800	0.0745	46.74	1.36
20.5	6.9	63	803	111	909	0.0743	64.36	2.25
21.0	7.5	76	765	89	853	0.0741	102.03	3.23
20.5	7.6	87	751	79	827	0.0741	124.65	4.47

[7]		[8]	[9]	[10]	[11]	[12]	[13]	[14]
Air/Fuel Wet	RHc	Air Dry	Air/Fuel Dry	O_2/Fuel	N_2/Fuel	O_2/Fuel	XS Air/Fuel	XS Air/Fuel
(lb/100lb)		(lb/min)	(lb/100lb)	(lb/100lb)	(lb/100lb)	(moles/100lb)	(lb/100lb)	(%)
1990.60	0.005	27.42	1981	458	1522	10.453	535.1	37.01
1414.75	0.005	33.30	1408	326	1082	10.453	-37.9	-2.62
1428.24	0.005	46.80	1421	329	1092	10.453	-24.5	-1.69
1385.39	0.005	62.95	1378	319	1059	10.453	-67.1	-4.64
3444.67	0.005	46.51	3427	793	2634	10.453	1981.9	137.10
2866.54	0.005	64.04	2852	660	2192	10.453	1406.6	97.31
3155.00	0.005	101.52	3139	726	2413	10.453	1693.7	117.16
2790.64	0.005	124.03	2777	643	2134	10.453	1331.1	92.08

[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
XS O_2/Fuel	H20/Fuel	CO_2+SO_2/Fuel	O_2/Fuel	N_2/Fuel	H_2Otot/Fuel	H_2Otot/Fuel	WFGtot/Fuel	DFGto/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(moles/100lb)	(moles/100lb)
3.9	0.553	7.236	14.323	54.058	6.95	125.15	72.12	65.16
-0.3	0.393	7.236	10.179	38.420	6.79	122.27	52.18	45.38
-0.2	0.397	7.236	10.276	38.786	6.80	122.34	52.64	45.85
-0.5	0.385	7.236	9.968	37.623	6.78	122.13	51.16	44.37
14.3	0.957	7.236	24.785	93.545	7.36	132.42	122.47	115.11
10.2	0.796	7.236	20.625	77.845	7.20	129.53	102.45	95.25
12.2	0.876	7.236	22.701	85.679	7.28	130.98	112.44	105.16
9.6	0.775	7.236	20.079	75.784	7.18	129.15	99.82	92.65

[24]	[25]	[26]	[27]	[28]	[28A]	[29]	[30]	[31]
CO	NO	NO2	SO_2	CO_2	CO_2	NO/Fuel	NO_2/Fuel	SO_2/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(lb/100lb)	(lb/100lb)
0.00494	0.04088	0.00200	0	7.227	m	1.227	0.092	0
0.00405	0.03379	0.00098	0	7.228	m	1.014	0.045	0
0.00433	0.03195	0.00072	0	7.227	m	0.959	0.033	0
0.00470	0.03053	0.00076	0	7.227	m	0.916	0.035	0
0.00719	0.07803	0.01422	0	7.225	5.890	2.341	0.654	0
0.00602	0.07652	0.01053	0	7.226	6.525	2.296	0.484	0
0.00794	0.08043	0.00931	0	7.224	7.835	2.414	0.428	0
0.00803	0.06953	0.00733	0	7.224	6.995	2.086	0.337	0

[32]	[33]	[34]	[35]	[36]	[37]	[38]
CO_2/Fuel	NOx/Fuel	fuel 1hr	NOx 1hr	Pwr	NOx out	Nox out
(lb/100lb)	(lb/100lb)	(lb)	(gal/hr)	(kW hr)	(g/kW-hr)	(kg/ton)
318.1	1.319	83.1	496.558	179.2	2.77	13
318.1	1.059	141.9	681.418	358.8	1.90	11
318.1	0.992	197.6	888.369	510.6	1.74	10
318.1	0.951	274.0	1181.597	679.2	1.74	10
318.0	2.996	81.4	1105.773	164.9	6.71	30
318.0	2.780	134.7	1698.243	337.1	5.04	28
317.9	2.842	194.0	2500.007	501.9	4.98	28
317.9	2.424	268.0	2945.358	668.5	4.41	24

Light Barge(pilot off;ECOM-port, ENERAC-stbd)				[4]				
Engine	Speed	HP	Fuel Flow	Fuel Flow	Air Flow	Air Temp	Air Temp	Air Press
	(rpm)	(ft lb)	(gal/hr)	(gal/min)	(CFM)	(deg F)	(deg C)	(in Hg)
stbd	742	245	12.0	0.199	430	83.0	28.3	30.6
stbd	942	477	19.9	0.331	345	83.1	28.4	30.6
stbd	1072	681	27.9	0.466	595	83.3	28.5	30.6
stbd	1178	933	39.2	0.653	930	83.7	28.7	30.6
port	742	228	11.6	0.193	628	83.7	28.7	30.3
port	942	462	19.3	0.322	893	84.4	29.1	30.3
port	1072	671	27.4	0.457	1370	84.8	29.3	30.3
port	1178	954	40.3	0.671	1827	84.4	29.1	30.3
(m) CO2 data were not collected on the port engine								
(n) stbd air flow readings were eratic during test								

						[2]	[3]	[6]
RH	CO2	CO	NO	NO2	NOx	Air Wet	Air Wet	Fuel
(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(lb/cuft)	(lb/min)	(lb/min)
19.5	5.3	64	683	123	805	0.0748	32.13	1.41
19.3	7.2	70	803	101	899	0.0747	25.78	2.35
19.5	7.6	80	814	78	886	0.0747	44.47	3.30
19.0	7.9	82	788	69	857	0.0747	69.45	4.63
19.5	m	84	722	37	752	0.0739	46.44	1.37
19.3	m	83	841	25	867	0.0739	66.01	2.28
19.5	m	87	786	19	805	0.0738	101.14	3.24
19.7	m	103	766	16	782	0.0739	134.91	4.76

[7]		[8]	[9]	[10]	[11]	[12]	[13]	[14]
Air/Fuel Wet	RHc	Air Dry	Air/Fuel Dry	O_2/Fuel	N_2/Fuel	O_2/Fuel	XS Air/Fuel	XS Air/Fuel
(lb/100lb)		(lb/min)	(lb/100lb)	(lb/100lb)	(lb/100lb)	(moles/100lb)	(lb/100lb)	(%)
2272	0.005	31.97	2261	523	1738	10.45	815.4	56.41
1098	0.005	25.65	1093	253	840	10.45	-352.8	-24.41
1347	0.005	44.25	1340	310	1030	10.45	-105.1	-7.27
1499	0.005	69.10	1492	345	1147	10.45	46.3	3.20
3393	0.005	46.21	3376	781	2595	10.45	1930.2	133.53
2890	0.005	65.68	2875	665	2210	10.45	1429.5	98.89
3124	0.005	100.64	3108	719	2389	10.45	1662.6	115.02
2836	0.005	134.23	2822	653	2169	10.45	1376.7	95.23

[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
XS O_2/Fuel	H20/Fuel	CO_2+SO_2/Fuel	O_2/Fuel	N_2/Fuel	H_2Otot/Fuel	H_2Otot/Fuel	WFGtot/Fuel	DFGto/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(moles/100lb)	(moles/100lb)
5.9	0.631	7.236	16.350	61.709	7.03	126.56	81.87	74.84
-2.6	0.305	7.236	7.902	29.824	6.71	120.69	41.21	34.51
-0.8	0.374	7.236	9.693	36.586	6.77	121.94	49.84	43.06
0.3	0.416	7.236	10.788	40.717	6.82	122.70	55.10	48.29
14.0	0.942	7.236	24.411	92.135	7.34	132.16	120.67	113.33
10.3	0.803	7.236	20.790	78.469	7.20	129.65	103.25	96.04
12.0	0.868	7.236	22.476	84.833	7.27	130.82	111.36	104.09
10.0	0.788	7.236	20.408	77.028	7.19	129.38	101.41	94.22

[24]	[25]	[26]	[27]	[28]	[28A]	[29]	[30]	[31]
CO	NO	NO2	SO_2	CO_2	CO_2	NO/Fuel	NO_2/Fuel	SO_2/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(lb/100lb)	(lb/100lb)
0.00478	0.05108	0.00923	0	7.227	3.929	1.533	0.425	0
0.00242	0.02772	0.00349	0	7.229	2.473	0.832	0.161	0
0.00345	0.03504	0.00337	0	7.228	3.280	1.051	0.155	0
0.00394	0.03805	0.00332	0	7.228	3.815	1.142	0.153	0
0.00954	0.08177	0.00417	0	7.222	m	2.454	0.192	0
0.00792	0.08076	0.00240	0	7.224	m	2.423	0.110	0
0.00902	0.08176	0.00196	0	7.223	m	2.454	0.090	0
0.00966	0.07217	0.00152	0	7.222	m	2.166	0.070	0

[32]	[33]	[34]	[35]	[36]	[37]	[38]
CO_2/Fuel	NOx/Fuel	fuel 1hr	NOx 1hr	Pwr	NOx out	Nox out
(lb/100lb)	(lb/100lb)	(lb)	(gal/hr)	(kW hr)	(g/kW-hr)	(kg/ton)
318.1	1.957	84.844	753.00	182.52	4.13	20
318.2	0.992	140.855	633.74	356.09	1.78	10
318.1	1.207	198.047	1083.48	507.78	2.13	12
318.1	1.294	277.928	1631.08	695.77	2.34	13
317.9	2.646	82.126	985.16	170.34	5.78	26
317.9	2.534	137.073	1574.73	344.78	4.57	25
317.9	2.544	194.266	2240.57	500.19	4.48	25
317.8	2.236	285.373	2892.88	711.31	4.07	22

Tug Pushing Light Barge(pilot on)				[4]							
Engine	Speed	HP	Fuel Flow	Fuel Flow	Air Flow	Air Temp	Air Temp	Air Press	RH	CO2	CO
	(rpm)	(ft lb)	(gal/hr)	(gal/min)	(CFM)	(deg F)	(deg C)	(in Hg)	(%)	(%)	(ppm)
stbd	742	244	11.88	0.198	410	76.7	24.8	30.4	21.5	m	79
stbd	942	475	19.87	0.331	305	75.4	24.1	30.4	22.0	m	99
stbd	1072	675	27.02	0.450	685	76.6	24.8	30.3	22.0	m	99
stbd	1178	889	36.58	0.610	961	76.5	24.7	30.4	22.0	m	98
port	742	223	11.52	0.192	599	75.8	24.4	30.3	21.5	5.3	67
port	942	451	19.20	0.320	725	72.6	22.6	30.4	22.2	7.1	79
port	1072	664	26.90	0.448	1106	75.5	24.2	30.4	22.0	7.7	83
port	1178	867	36.65	0.611	1383	75.8	24.3	30.3	22.0	7.7	89

			[2]	[3]	[6]	[7]		[8]	[9]	[10]	[11]
NO	NO_2	NOx	Air Wet	Air Wet	Fuel	Air/Fuel W	RHc	Air Dry	Air/Fuel D	O_2/Fuel	N_2/Fuel
(ppm)	(ppm)	(ppm)	(lb/cuft)	(lb/min)	(lb/min)	(lb/100lb)		(lb/min)	(lb/100lb)	(lb/100lb)	(lb/100lb)
621	29	649	0.0752	30.82	1.40	2194.83	0.005	30.67	2184	505	1679
682	20	698	0.0752	22.92	2.35	976.20	0.005	22.80	971	225	747
647	14	662	0.0750	51.36	3.19	1608.85	0.005	51.11	1601	370	1230
663	13	675	0.0752	72.28	4.32	1672.12	0.005	71.92	1664	385	1279
679	126	805	0.0751	44.97	1.36	3304.64	0.005	44.75	3288	761	2527
799	118	927	0.0757	54.88	2.27	2418.90	0.005	54.61	2407	557	1850
753	97	851	0.0752	83.20	3.18	2617.39	0.005	82.78	2604	603	2002
744	89	832	0.0751	103.88	4.33	2398.69	0.005	103.36	2387	552	1834

[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]
O_2/Fuel	XS Air/Fuel	XS Air/Fuel	XS O_2/Fuel	H20/Fuel	CO_2+SO_2/Fuel	O_2/Fuel	N_2/Fuel	H_2Otot/Fuel	H_2Otot/Fuel
(moles/100l	(lb/100lb)	(%)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb	(moles/100lb)	(moles/100lb)	(lb/100lb)
10.453	738.3	51.07	5.3	0.610	7.236	15.792	59.604	7.01	126.17
10.453	-474.3	-32.81	-3.4	0.271	7.236	7.024	26.510	6.67	120.08
10.453	155.2	10.74	1.1	0.447	7.236	11.576	43.691	6.85	123.24
10.453	218.2	15.09	1.6	0.464	7.236	12.031	45.409	6.86	123.56
10.453	1842.5	127.46	13.3	0.918	7.236	23.777	89.743	7.32	131.72
10.453	961.2	66.50	7.0	0.672	7.236	17.404	65.689	7.07	127.29
10.453	1158.7	80.16	8.4	0.727	7.236	18.832	71.080	7.13	128.29
10.453	941.1	65.10	6.8	0.666	7.236	17.259	65.140	7.07	127.19

[22]	[23]	[24]	[25]	[26]	[27]	[28]	[28A]	[29]	[30]
WFGtot/Fuel	DFGto/Fuel	CO	NO	NO2	SO_2	CO_2	CO_2	NO/Fuel	NO_2/Fuel
(moles/100lb	(moles/100lb)	(moles/100lb)	(moles/100lb	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(lb/100lb)
79.19	72.18	0.00571	0.04484	0.00206	0	7.226	m	1.345	0.095
36.99	30.32	0.00301	0.02066	0.00060	0	7.229	m	0.620	0.028
58.90	52.05	0.00516	0.03365	0.00075	0	7.227	m	1.010	0.034
61.09	54.22	0.00533	0.03592	0.00072	0	7.226	m	1.078	0.033
117.62	110.30	0.00735	0.07488	0.01388	0	7.224	5.83	2.247	0.639
86.95	79.88	0.00628	0.06378	0.00944	0	7.225	5.66	1.914	0.434
93.82	86.70	0.00721	0.06527	0.00837	0	7.224	6.63	1.959	0.385
86.25	79.18	0.00705	0.05891	0.00705	0	7.225	6.11	1.768	0.324

[31]	[32]	[33]	[34]	[35]	[36]	[37]	[38]
SO_2/Fuel	CO_2/Fuel	NOx/Fuel	fuel 1hr	NOx 1hr	Pwr	NOx out	NOx out
(lb/100lb)	(lb/100lb)	(lb/100lb)	(lb)	(gal/hr)	(kW hr)	(g/kW-hr)	(kg/ton)
0	318.0	1.440	84.253	550.105	181.651	3.03	14
0	318.1	0.648	140.855	413.622	354.5987	1.17	6
0	318.0	1.044	191.548	906.780	503.177	1.80	10
0	318.0	1.111	259.376	1306.824	663.4427	1.97	11
0	318.0	2.885	81.653	1068.254	166.358	6.42	29
0	318.0	2.348	136.128	1449.320	336.6947	4.30	23
0	318.0	2.343	190.721	2026.429	495.5927	4.09	23
0	318.0	2.092	259.849	2464.742	646.782	3.81	21

Tug pulling light barge(pilot on)																					
Run Seq	Pilot/Eng	Date/Time	O2%	COppm	CO2ppm	NOppm	NO2ppm	NOxppm	SO2ppm	STemp	CFM	Fdeg	Hg"	RH%	CGHP	CGTQ	CGRPM	STgal/Hr	STRPM	STHP	GPSsp
B1.100	on/stbd	5-13/0747	10.7	125	-	777	17	784	0	678	804	73.4	30.4	22	902	201	236	36.9	1174	674	9.1
B2.100	on/stbd	5-13/0749	10.6	130	-	777	16	793	0	676	395	74.3	30.4	22	907	202	237	37.5	1174	654	8.8
B3.100	on/stbd	5-13/0751	10.6	125	-	778	15	798	0	678	443	75.1	30.4	22	912	203	237	36.9	1172	654	8.9
B1.100	on/port	5-13/0750	10.5	81	7.8	745	93	838	-	638	617	71.5	30.5	22	890	196	238	38.3	1178	676	9.1
B2.100	on/port	5-13/0752	10.5	80	7.9	752	95	839	-	638	596	71.4	30.4	22	869	195	236	36.8	1170	646	8.8
B3.100	on/port	5-13/0754	10.5	84	7.9	744	96	843	-	638	544	71.9	30.4	22	887	196	238	37.6	1174	654	8.9
B1.91	on/stbd	5-13/0803	11	90	-	775	18	788	0	654	480	73.3	30.3	22	693	170	216	27.3	1070	466	9.3
B2.91	on/stbd	5-13/0804	10.9	115	-	775	19	798	0	652	279	73.6	30.3	22	679	167	214	27	1060	450	9
B3.91	on/stbd	5-13/0806	10.9	120	-	773	20	798	0	649	397	74.6	30.3	22	688	170	214	27	1060	456	8
B1.91	on/port	5-13/0805	10.6	85	7.8	769	102	873	-	612	519	71.7	30.3	22	670	165	216	27.2	1069	456	9.3
B2.91	on/port	5-13/0807	10.6	86	7.8	763	101	862	-	612	426	72.4	30.4	22	674	166	216	26.7	1063	452	9
B3.91	on/port	5-13/0809	10.6	84	7.8	746	100	857	-	612	573	73.5	30.4	22	673	167	215	27.1	1063	452	8
B1.80	on/stbd	5-13/0823	11.6	105	-	825	24	834	0	578	161	73.8	30.3	22	459	130	186	19.1	919	292	7.4
B2.80	on/stbd	5-13/0825	11.8	110	-	815	26	840	0	575	164	74.4	30.3	22	471	133	187	19.7	924	298	7.8
B3.80	on/stbd	5-13/0827	11.8	110	-	836	27	863	0	575	117	73.6	30.3	22	480	134	189	20.6	942	316	7.7
B1.80	on/port	5-13/0828	11.4	103	7.2	800	124	950	-	535	352	73.4	30.4	22	438	127	186	18.7	920	284	7.4
B2.80	on/port	5-13/0830	11.5	83	7.1	802	124	926	-	532	354	72.6	30.4	22	438	126	187	18.7	924	284	7.8
B3.80	on/port	5-13/0832	11.3	83	7.2	788	120	906	-	542	340	72.9	30.4	22	462	131	190	20.1	942	306	7.7
B1.63	on/stbd	5-13/0843	14	100	-	740	35	773	0	429	196	75.5	30.4	22	252	89	150	11.9	741	152	5.3
B2.63	on/stbd	5-13/0846	13.9	100	-	758	37	793	0	430	195	75.3	30.4	22	249	89	149	11.8	736	142	5.7
B3.63	on/stbd	5-13/0848	13.9	100	-	745	39	788	0	427	232	75	30.3	22	256	90	150	12.2	745	154	5.4
B1.63	on/port	5-13/0845	13.6	67	5.5	691	130	825	-	406	281	74.7	30.4	22	230	84	151	11.7	741	144	5.3
B2.63	on/port	5-13/0847	13.7	69	5.5	689	135	823	-	405	292	74.7	30.4	22	227	84	149	11.6	737	144	5.7
B3.63	on/port	5-13/0849	13.6	72	5.5	694	138	830	-	406	309	73.3	30.4	22	232	85	151	11.7	742	144	5.4
D1.80	on/stbd	5-13/0908	14.5	85	-	532	15	548	0	583	143	77.1	30.4	22	478	133	190	19.8	940	310	7.2
D2.80	on/stbd	5-13/0910	14.5	90	-	541	14	552	0	582	169	77.5	30.4	22	482	134	190	20	940	316	7.9
D3.80	on/stbd	5-13/0912	14.5	95	-	540	13	553	0	584	160	76.1	30.4	22	482	134	190	20	942	306	7.2
D1.80	on/port	5-13/0903	11.6	65	7	797	108	926	-	527	371	73.1	30.4	22	453	126	190	19	938	292	7.2
D2.80	on/port	5-13/0905	11.6	69	7	795	116	928	-	528	389	71.9	30.4	22	455	126	190	19.4	941	296	7.9
D3.80	on/port	5-13/0907	11.6	69	7	809	117	926	-	528	369	71.9	30.3	23	462	130	191	19.3	942	296	7.2
D1.91	on/stbd	5-13/0925	14.1	80	-	506	12	518	0	646	406	79.5	30.4	22	666	163	215	27.1	1065	446	8.2
D2.91	on/stbd	5-13/0927	14	95	-	521	9	532	0	644	203	78.7	30.3	22	663	163	215	27.2	1065	452	8.4
D3.91	on/stbd	5-13/0929	14	95	-	529	8	536	0	642	250	79.7	30.4	22	658	162	214	26.5	1059	438	9.3
D1.91	on/port	5-13/0926	11	83	7.5	750	90	841	-	592	569	78	30.4	22	660	163	216	26.7	1070	450	8.2
D2.91	on/port	5-13/0928	11	83	7.5	745	93	838	-	587	581	77.7	30.4	22	659	162	216	27	1069	450	8.4
D3.91	on/port	5-13/0930	11	78	7.5	744	93	835	-	587	649	79.8	30.3	22	650	160	216	26.7	1069	444	9.3
D1.100	on/stbd	5-13/0952	13.4	70	-	537	11	546	0	676	372	78.1	30.4	22	862	192	236	35.9	1170	622	10.1
D2.100	on/stbd	5-13/0955	13.4	70	-	552	11	561	0	676	401	78.8	30.4	22	877	192	236	36.2	1163	632	9.5
D3.100	on/stbd	5-13/0957	13.4	70	-	554	10	565	0	677	469	79.3	30.4	22	876	195	236	36.1	1168	634	9
D1.100	on/port	5-13/0954	10.9	94	7.5	736	80	815	-	573	781	79.7	30.3	22	853	191	237	36.1	1176	632	10.1
D2.100	on/port	5-13/0956	10.8	95	7.6	737	84	824	-	574	834	79.4	30.2	22	870	194	237	36.4	1175	644	9.5
D3.100	on/port	5-13/0958	10.8	100	7.6	750	86	832	-	576	776	80.6	30.2	22	833	186	235	34.7	1160	604	9
D1.63	on/stbd	5-13/1023	16.3	55	-	469	19	490	0	397	205	77.7	30.5	21	220	79	148	11.4	752	148	6.1
D2.63	on/stbd	5-13/1025	16.2	60	-	493	20	513	0	407	192	78.2	30.4	21	240	84	150	12	748	150	6.1
D3.63	on/stbd	5-13/1027	16	60	-	522	21	538	0	416	210	78.2	30.4	21	244	86	152	12	749	150	5.8
D1.63	on/port	5-13/1024	14.4	61	5	664	111	769	-	369	292	76.8	30.3	21	205	48	177	11.2	730	134	6.1
D2.63	on/port	5-13/1026	14.2	65	5.1	659	118	785	-	377	334	78.9	30.2	21	219	81	151	11.4	748	138	6.1
D3.63	on/port	5-13/1028	14.1	66	5.1	676	123	799	-	382	289	76.6	30.2	21	225	82	152	11.5	749	140	5.8

Tug pulling light barge(pilot off)																					
Run Seq	Pilot/Eng	Date/Time	O2%	COppm	CO2ppm	NOppm	NO2ppm	NOxppm	SO2ppm	STemp	CFM	Fdeg	Hg"	RH%	CGHP	CGTQ	CGRPM	STgal/Hr	STRPM	STHP	GPSsp
A1.63	off/stbd	5-13/1040	15 3	70	-	581	35	610	0	408	162	76.6	30.4	21	234	83	150	11.6	742	140	6.2
A2.63	off/stbd	5-13/1042	15 3	75	-	594	32	629	0	408	114	78	30.5	21	234	83	150	11.6	743	144	6.4
A3.63	off/stbd	5-13/1047	15 3	75	-	593	31	611	0	411	211	76.6	30.5	22	232	82	150	11.6	742	140	6.8
A1.63	off/port	5-13/1041	14 2	59	5	671	119	788	-	377	300	77.3	30.2	21	220	81	151	11.4	746	138	6.2
A2.63	off/port	5-13/1043	14 2	60	5 1	668	124	791	-	377	309	76.5	30.2	21	218	80	151	11.4	745	138	6.4
A3.63	off/port	5-13/1045	14.3	62	5	649	123	777	-	374	322	74.4	30.2	22	213	75	151	11.4	745	138	6.8
A1.80	off/stbd	5-13/1055	13	75	-	664	28	694	0	573	250	77.3	30.4	21	482	133	191	20.2	946	314	8.3
A2.80	off/stbd	5-13/1057	13 1	80	-	678	21	699	0	570	315	77.3	30.4	21	475	131	191	19.7	946	302	8.1
A3.80	off/stbd	5-13/1059	13.1	85	-	672	19	699	0	567	228	76.4	30.4	21	468	130	191	19.7	946	304	8.4
A1.80	off/port	5-13/1056	12	61	6.8	801	106	903	-	514	432	76.6	30.2	21	452	127	192	18.9	946	294	8.3
A2.80	off/port	5-13/1058	12	64	6.7	796	111	907	-	511	436	79	30.2	21	444	194	192	18.7	946	284	8.1
A3.80	off/port	5-13/1100	12.2	61	6.6	789	113	895	-	505	439	78.8	30.2	21	438	123	191	18.7	946	284	8.4
A1.91	off/stbd	5-13/1109	12.5	80	-	616	19	648	0	637	188	77.6	30.4	21	675	164	217	27.6	1073	462	9.2
A2.91	off/stbd	5-13/1111	12.6	95	-	624	13	641	0	638	336	77.6	30.4	21	672	164	217	27.3	1073	462	9
A3.91	off/stbd	5-13/1113	12 6	95	-	639	12	651	0	638	291	78.2	30.4	21	677	165	217	27.3	1073	450	9.6
A1.91	off/port	5-13/1110	11.3	71	7.3	758	84	839	-	576	682	79.5	30.2	21	651	160	217	27	1071	451	9.2
A2.91	off/port	5-13/1112	11.2	77	7.3	757	89	851	-	573	703	79.3	30.2	21	649	160	217	27	1071	450	9
A3.91	off/port	5-13/1114	11 2	75	7.3	760	91	856	-	573	691	79.1	30.2	21	655	161	217	26.8	1072	446	9.6
A1.100	off/stbd	5-13/1124	12.2	85	-	636	16	658	0	677	349	79.7	30.5	20	895	198	238	37.3	1178	664	10.3
A2.100	off/stbd	5-13/1126	12.2	95	-	646	13	662	0	676	403	79.5	30.5	20	903	200	238	37.4	1177	670	9.3
A3.100	off/stbd	5-13/1128	12 2	100	-	655	11	661	0	676	373	79.9	30.5	20	906	201	238	37.4	1177	664	9
A1.100	off/port	5-13/1125	11	75	7.4	749	75	814	-	612	833	80.4	30.2	20	873	194	238	37	1176	644	10.3
A2.100	off/port	5-13/1127	10 9	85	7.5	753	83	836	-	592	790	80.4	30.2	20	882	197	238	37	1175	650	9.3
A3.100	off/port	5-13/1129	10.9	87	7.5	760	84	845	-	585	840	78.9	30.2	20	883	197	238	37.3	1177	646	9
C1.63	off/stbd	5-13/1154	14.7	75	-	655	29	684	0	430	190	80.5	30.5	20	247	87	150	11.9	743	148	5.7
C2.63	off/stbd	5-13/1156	14.7	80	-	670	28	704	0	438	245	80.8	30.5	21	247	87	150	11.9	743	146	5.3
C3.63	off/stbd	5-13/1158	14.7	80	-	671	29	696	0	429	179	80.1	30.5	21	247	87	150	11.9	742	152	4.7
C1.63	off/port	5-13/1151	14	66	5.2	694	123	822	-	402	334	81.5	30.3	20	225	83	151	11.5	742	140	5.7
C2.63	off/port	5-13/1153	14	64	5.2	696	125	813	-	399	301	80.1	30.2	21	224	82	151	11.5	742	142	5.3
C3.63	off/port	5-13/1155	14	64	5.2	689	127	810	-	397	317	80.8	30.2	21	226	83	151	11.7	742	142	4.7
C1.100	off/stbd	5-13/1203	10.7	115	-	714	25	742	0	677	465	80.9	30.5	21	918	203	238	38.9	1178	682	9.3
C2.100	off/stbd	5-13/1205	10.7	125	-	734	20	755	0	680	443	81.4	30.5	21	923	204	238	38.3	1179	682	9.3
C3.100	off/stbd	5-13/1207	10.7	115	-	743	18	761	0	683	318	80.3	30.5	21	918	202	238	38.6	1178	676	9.5
C1.100	off/port	5-13/1204	10.9	85	7.6	745	73	794	-	605	887	80.5	30.2	21	918	204	239	38.3	1179	670	9.3
C2.100	off/port	5-13/1206	10.8	96	7.6	749	79	826	-	587	871	81.2	30.2	21	914	203	239	38.6	1179	670	9.3
C3.100	off/port	5-13/1208	10.8	92	7.7	747	81	844	-	586	823	81.9	30.2	21	907	201	239	38.6	1179	676	9.5
C1.91	off/stbd	5-13/1217	10.8	85	-	758	20	774	0	664	444	81.1	30.5	21	696	169	216	28.1	1071	466	8.7
C2.91	off/stbd	5-13/1219	10.7	105	-	767	16	781	0	661	374	81.5	30.5	21	692	169	217	28.8	1072	468	8.4
C3.91	off/stbd	5-13/1221	10.7	107	-	777	14	785	0	658	251	81.3	30.5	21	695	169	216	28.1	1072	468	7.8
C1.91	off/port	5-13/1218	10.9	70	7.6	773	84	851	-	587	783	83.3	30.3	21	709	172	219	27.5	1071	460	8.7
C2.91	off/port	5-13/1220	10.8	80	7.6	771	91	862	-	565	664	83.7	30.3	21	690	165	218	28	1076	470	8.4
C3.91	off/port	5-13/1221	10.8	80	7.6	770	92	861	-	560	605	83.3	30.3	21	683	167	217	27.9	1072	472	7.8
C1.80	off/stbd	5-13/1228	11.4	95	-	817	20	842	0	598	184	80.7	30.5	20	486	135	191	20.3	944	316	6.1
C2.80	off/stbd	5-13/1230	11.4	100	-	820	20	840	0	596	150	86.1	30.5	20	486	134	191	20.1	943	312	6.7
C3.80	off/stbd	5-13/1232	11.5	100	-	817	21	838	0	596	215	84.9	30.6	20	489	136	190	20.1	943	312	6.6
C1.80	off/port	5-13/1229	11.6	66	7	823	104	917	-	541	468	82.8	30.3	20	459	125	191	19.3	941	296	6.1
C2.80	off/port	5-13/1231	11.7	66	7	806	113	906	-	536	409	83	30.3	20	456	126	191	19.1	943	296	6.7
C3.80	off/port	5-13/1233	11.6	61	7	805	116	924	-	531	416	83.1	30.3	20	462	130	190	19.3	942	296	6.6
B1.100	off/stbd	5-13/1241	10.6	91	7.8	751	74	817	-	649	502	81.1	30.6	21	942	206	240	40.2	1189	708	8.3
B2.100	off/stbd	5-13/1243	10.5	91	7.8	755	75	832	-	653	356	83	30.6	20	953	209	240	39.9	1189	714	8.3
B3.100	off/stbd	5-13/1245	10.4	91	7.9	756	76	853	-	655	593	82.4	30.5	20	953	209	240	39.8	1189	708	8.2
Swapped emission analyzers, Ecom-port, Enerac-stbd																					
B1.100	off/port	5-13/1242	10.6	100	-	763	15	778	0	680	862	81.6	30.3	21	950	206	242	40.4	1195	718	8.3
B2.100	off/port	5-13/1244	10.6	105	-	763	14	775	0	682	944	82.3	30.3	20	970	212	242	40.7	1196	732	8.3
B3.100	off/port	5-13/1246	10.6	100	-	769	14	790	0	682	894	82.6	30.3	20	959	209	242	40.8	1196	718	8.2

B1.91	off/stbd	5-13/1253	10.9	73	7.5	821	75	878	-	618	362	81.8	30.5	20	669	163	216	27.3	1071	462	7.3
B2.91	off/stbd	5-13/1255	10.7	80	7.7	810	80	869	-	620	397	82	30.6	20	692	168	217	27.8	1072	462	7.4
B3.91	off/stbd	5-13/1256	10.6	80	7.8	820	79	894	-	622	355	84.5	30.6	20	684	167	216	27.6	1072	462	7.7
B1.91	off/port	5-13/1252	11	70	-	785	18	803	0	649	692	84.2	30.3	20	660	163	217	27.3	1071	456	7.3
B2.91	off/port	5-13/1254	10.8	80	-	787	18	816	0	651	741	83.6	30.3	20	673	166	216	27.6	1071	462	7.4
B3.91	off/port	5-13/1256	10.7	80	-	801	17	812	0	653	672	84.3	30.3	20	676	166	216	27.3	1071	456	7.7
B1.80	off/stbd	5-13/1305	11.4	70	7.2	818	97	892	-	556	170	82.4	30.6	20	479	133	190	20.1	943	316	6.5
B2.80	off/stbd	5-13/1306	11.3	75	7.2	802	103	900	-	558	130	85.3	30.6	20	481	133	191	20.1	943	312	6.9
B3.80	off/stbd	5-13/1308	11.3	72	7.3	795	103	900	-	559	230	81.6	30.6	19	483	134	191	19.8	944	308	6.3
B1.80	off/port	5-13/1304	11.5	80	-	830	26	857	0	586	453	84.9	30.3	20	460	130	191	19.3	941	296	6.5
B2.80	off/port	5-13/1306	11.4	85	-	850	24	871	0	584	453	84.5	30.3	20	462	130	191	19.3	940	296	6.9
B3.80	off/port	5-13/1307	11.5	80	-	852	24	876	0	584	459	85.1	30.3	19	464	130	191	19.3	942	296	6.3
B1.63	off/stbd	5-13/1315	13.9	66	5.3	694	120	812	-	418	235	84.9	30.6	20	247	87	151	12	745	150	5.1
B2.63	off/stbd	5-13/1317	13.9	66	5.3	684	122	806	-	413	260	83	30.6	20	244	86	151	12	745	150	4.7
B3.63	off/stbd	5-13/1319	13.9	61	5.3	679	123	802	-	410	174	83.2	30.6	20	248	87	151	12	745	150	5.1
B1.63	off/port	5-13/1314	13.8	85	-	732	34	752	0	440	309	83.9	30.3	20	230	84	151	11.5	742	148	5.1
B2.63	off/port	5-13/1316	13.8	80	-	725	36	765	0	435	320	83.4	30.3	20	228	84	151	11.5	742	144	4.7
B3.63	off/port	5-13/1318	13.9	85	-	721	37	752	0	431	322	84.1	30.3	20	232	84	151	11.7	742	144	5.1
A1.63	off/stbd	5-13/1356	14.1	63	5.2	678	123	800	-	390	175	82.8	30.6	19	243	85	151	11.8	747	146	5
A2.63	off/stbd	5-13/1358	14	63	5.2	676	125	801	-	395	206	82.1	30.6	19	243	85	151	12.2	746	150	5.3
A3.63	off/stbd	5-13/1400	14	64	5.2	684	127	811	-	398	239	81.8	30.6	19	243	85	151	11.8	745	150	5.3
A1.63	off/port	5-13/1355	13.9	85	-	710	35	737	0	419	309	84.1	30.3	19	226	83	151	11.4	747	140	5
A2.63	off/port	5-13/1357	13.9	85	-	721	39	744	0	420	323	83.1	30.3	19	227	83	151	11.8	742	144	5.3
A3.63	off/port	5-13/1359	13.9	85	-	720	40	760	0	421	301	83.8	30.3	19	227	83	151	11.6	742	144	5.3
A1.80	off/stbd	5-13/1406	11.5	68	7.1	823	98	909	-	531	181	83.4	30.6	19	473	131	191	19.1	940	310	6.4
A2.80	off/stbd	5-13/1408	11.5	68	7.1	793	102	903	-	536	141	82.7	30.6	19	472	131	190	20.1	942	310	6.7
A3.80	off/stbd	5-13/1409	11.5	68	7.1	788	104	888	-	538	183	83	30.5	19	476	132	190	20	942	312	6.9
A1.80	off/port	5-13/1407	11.6	85	-	833	26	864	0	568	455	84.2	30.4	19	464	130	191	19.1	942	298	6.4
A2.80	off/port	5-13/1409	11.6	85	-	840	25	867	0	567	421	82.9	30.3	19	460	125	191	19.4	943	302	6.7
A3.80	off/port	5-13/1410	11.6	80	-	840	25	867	0	569	439	84.9	30.3	19	463	130	191	19.6	942	302	6.9
A1.91	off/stbd	5-13/1418	11	80	7.5	797	77	888	-	602	154	84.1	30.6	19	678	165	217	27.9	1074	466	8.1
A2.91	off/stbd	5-13/1420	10.8	84	7.6	804	79	884	-	608	203	83.8	30.6	19	682	166	217	28.5	1073	468	8.4
A3.91	off/stbd	5-13/1421	10.8	84	7.6	830	80	900	-	611	315	83.7	30.6	19	679	165	217	28.5	1075	462	8.7
A1.91	off/port	5-13/1416	11	95	-	775	21	796	0	636	671	84.2	30.3	19	669	164	217	27.3	1073	462	8.1
A2.91	off/port	5-13/1417	11	95	-	778	20	800	0	639	662	86.5	30.3	19	675	165	217	27.3	1072	462	8.4
A3.91	off/port	5-13/1419	10.9	100	-	787	19	805	0	644	673	85.7	30.3	19	670	165	217	27.6	1072	462	8.7
A1.100	off/stbd	5-13/1431	10.4	83	7.9	790	68	860	-	628	507	83.7	30.6	19	922	201	241	39.3	1191	686	9
A2.100	off/stbd	5-13/1432	10.4	81	7.9	788	69	857	-	630	461	83.9	30.6	19	929	203	241	39.3	1191	690	9.2
A3.100	off/stbd	5-13/1434	10.4	81	7.9	786	69	855	-	633	427	83.6	30.6	19	947	207	241	39	1190	696	9.6
A1.100	off/port	5-13/1428	10.7	100	-	761	19	775	0	680	916	84.1	30.3	19	939	205	243	40.2	1198	702	9
A2.100	off/port	5-13/1430	10.7	105	-	766	18	785	0	680	909	82.5	30.3	19	944	206	243	39.2	1186	694	9.2
A3.100	off/port	5-13/1431	10.7	105	-	774	17	791	0	681	955	93.4	30.3	19	959	205	243	40.2	1192	690	9.6

C-22

Appendix D
Free Tug Emission Calculations

[D-3 through D-8 present the NOx calculations of the tug running by itself without the engine speed pilot engaged;
D-9 through D-10 present the raw data sheet for the tug running by itself without the engine speed pilot engaged]

[BLANK]

Free Running Tug w/o Barge(pilot off)				[4]				
Engine	Speed	HP	Fuel Flow	Fuel Flow	Air Flow	Air Temp	Air Temp	Air Press
	(rpm)	(ft lb)	(gal/hr)	(gal/min)	(CFM)	(deg F)	(deg C)	(in Hg)
stbd	742	139	10.93	0.182	388	80.9	27.2	30.8
stbd	942	308	17.46	0.291	303	81.2	27.4	30.8
stbd	1072	478	24.40	0.407	529	82.0	27.8	30.8
stbd	1178	701	34.04	0.567	671	81.8	27.7	30.8
port	742	152	10.72	0.179	570	80.4	26.9	30.7
port	942	341	17.12	0.285	775	79.0	26.1	30.7
port	1072	511	23.44	0.391	1071	77.7	25.4	30.6
port	1178	726	32.82	0.547	1399	77.9	25.5	30.6
(m) CO2 data were not collected on the port engine								

						[2]	[3]	[6]
RH (%)	CO2 (%)	CO (ppm)	NO (ppm)	NO_2 (ppm)	NOx (ppm)	Air Wet (lb/cuft)	Air Wet (lb/min)	Fuel (lb/min)
21.3	4.6	73	513	98	606	0.0756	29.31	1.29
21.3	6.2	60	666	105	770	0.0756	22.92	2.06
21.3	7.0	77	692	83	776	0.0755	39.94	2.88
21.7	7.4	111	647	71	718	0.0755	50.64	4.02
21.3	m	82	534	24	558	0.0754	42.95	1.27
21.3	m	61	719	26	742	0.0755	58.50	2.02
21.3	m	66	721	21	743	0.0756	80.97	2.77
21.7	m	113	663	22	686	0.0755	105.68	3.88

[7]		[8]	[9]	[10]	[11]	[12]	[13]	[14]
Air/Fuel Wet	RHc	Air Dry	Air/Fuel Dry	O_2/Fuel	N_2/Fuel	O_2/Fuel	XS Air/Fuel	XS Air/Fuel
(lb/100lb)		(lb/min)	(lb/100lb)	(lb/100lb)	(lb/100lb)	(moles/100lb)	(lb/100lb)	(%)
2268.46	0.005	29.16	2257	522	1735	10.453	811.5	56.14
1111.23	0.005	22.81	1106	256	850	10.453	-339.9	-23.51
1385.31	0.005	39.74	1378	319	1059	10.453	-67.2	-4.65
1258.83	0.005	50.39	1253	290	963	10.453	-193.0	-13.35
3391.80	0.005	42.74	3375	781	2594	10.453	1929.3	133.46
2891.49	0.005	58.21	2877	666	2211	10.453	1431.5	99.02
2922.61	0.005	80.56	2908	673	2235	10.453	1462.4	101.17
2724.66	0.005	105.15	2711	627	2084	10.453	1265.5	87.54

[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
XS O_2/Fuel	H20/Fuel	CO_2+SO_2/Fuel	O_2/Fuel	N_2/Fuel	H_2Otot/Fuel	H_2Otot/Fuel	WFGtot/Fuel	DFGto/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(moles/100lb)	(moles/100lb)
5.9	0.630	7.236	16.322	61.604	9.70	174.56	84.41	74.71
-2.5	0.309	7.236	7.995	30.177	7.91	142.44	42.87	34.96
-0.5	0.385	7.236	9.967	37.620	8.34	150.05	52.71	44.37
-1.4	0.350	7.236	9.057	34.186	8.14	146.54	48.17	40.03
14.0	0.942	7.236	24.404	92.110	11.43	205.73	124.73	113.30
10.4	0.803	7.236	20.805	78.523	10.66	191.85	106.77	96.11
10.6	0.812	7.236	21.028	79.368	10.71	192.71	107.89	97.18
9.2	0.757	7.236	19.604	73.993	10.40	187.22	100.78	90.38

[24]	[25]	[26]	[27]	[28]	[28A]	[29]	[30]	[31]
CO	NO	NO2	SO_2	CO_2	CO_2	NO/Fuel	NO_2/Fuel	SO_2/Fuel
(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(moles/100lb)	(lb/100lb)	(lb/100lb)	(lb/100lb)
0.00545	0.03833	0.00734	0	7.226	3.420	1.150	0.338	0
0.00210	0.02327	0.00366	0	7.230	2.154	0.698	0.168	0
0.00343	0.03070	0.00369	0	7.228	3.116	0.921	0.170	0
0.00445	0.02590	0.00283	0	7.227	2.975	0.777	0.130	0
0.00925	0.06050	0.00277	0	7.222	m	1.816	0.127	0
0.00587	0.06908	0.00247	0	7.226	m	2.073	0.113	0
0.00637	0.07003	0.00200	0	7.225	m	2.102	0.092	0
0.01024	0.05988	0.00202	0	7.221	m	1.797	0.093	0

[32]	[33]	[34]	[35]	[36]	[37]	[38]
CO_2/Fuel	NOx/Fuel	fuel 1hr	NOx 1hr	Pwr	NOx out	Nox out
(lb/100lb)	(lb/100lb)	(lb)	(gal/hr)	(kW hr)	(g/kW-hr)	(kg/ton)
318.0	1.488	77.517	522.862	103.694	5.04	15
318.2	0.867	123.760	486.336	229.768	2.12	9
318.1	1.091	172.996	855.953	356.588	2.40	11
318.1	0.907	241.375	993.109	522.946	1.90	9
317.9	1.943	75.981	669.333	113.392	5.90	19
318.0	2.187	121.397	1203.483	254.386	4.73	22
318.0	2.193	166.221	1653.114	381.206	4.34	22
317.8	1.890	232.710	1993.932	541.596	3.68	19

[FREE TUG]

Run Seq	Pilot/Eng	Date/Time	O2%	COppm	CO2ppm	NOppm	NO2ppm	NOxppm	SO2ppm	STemp	CFM	Fdeg	Hg"	RH%	CGHP	CGTQ	CGRPM	STgal/Hr	STRPM	STHP	GPSsp
A1.63	off/stbd	5-14/2338	15	65	4.5	524	91	621	-	359	-	-	-	21	142	50	150	11	744	130	6.2
A2.63	off/stbd	5-14/2341	15	76	4.5	512	97	610	-	356	-	-	-	21	142	50	151	11	743	126	6.6
A3.63	off/stbd	5-14/2342	15	76	4.5	503	99	602	-	354	-	-	-	21	140	49	151	10.8	744	126	6.4
A1.63	off/port	5-14/2331	14.8	75	-	526	23	548	0	384	311	79.9	30.8	21	151	57	151	10.6	743	122	6.2
A2.63	off/port	5-14/2333	14.8	80	-	529	22	550	0	381	257	80.7	30.8	21	151	57	151	10.6	744	122	6.6
A3.63	off/port	5-14/2335	14.8	85	-	539	22	561	0	378	270	80	30.8	21	150	56	151	10.6	742	122	6.4
A1.80	off/stbd	5-14/2349	12.9	58	6.1	669	102	772	-	467	143	80	30.8	21	301	84	190	17.4	941	256	7.3
A2.80	off/stbd	5-14/2350	12.9	59	6.1	666	103	770	-	469	165	80.8	30.8	21	300	83	190	17.6	941	256	6.7
A3.80	off/stbd	5-14/2351	12.8	56	6.1	662	105	767	-	472	167	81.9	30.8	21	305	84	191	17.6	941	256	8
A1.80	off/port	5-14/2345	12.8	55	-	720	32	747	0	493	322	79.9	30.7	21	333	94	191	17.2	944	258	7.3
A2.80	off/port	5-14/2346	12.9	55	-	724	28	742	0	495	376	79.5	30.7	21	334	94	191	16.9	945	248	6.7
A3.80	off/port	5-14/2347	12.8	60	-	719	27	751	0	495	387	79.9	30.7	21	337	95	191	17.1	944	244	8
A1.91	off/stbd	5-14/2359	11.8	78	6.9	688	79	768	-	551	371	82	30.8	21	470	114	217	24	1074	396	8.7
A2.91	off/stbd	5-14/2400	11.7	76	7	697	82	779	-	557	305	81	30.8	21	476	116	217	24.8	1073	390	9.3
A3.91	off/stbd	5-14/2401	11.7	78	7	689	83	773	-	557	274	81.3	30.8	21	475	115	216	24.8	1073	400	9.9
A1.91	off/port	5-14/2356	12.8	55	-	708	25	735	0	576	484	75.8	30.7	21	515	127	217	23.4	1074	384	8.7
A2.91	off/port	5-14/2357	11.9	65	-	710	23	743	0	576	379	76.9	30.7	21	512	126	217	23.4	1074	378	9.3
A3.91	off/port	5-14/2358	11.9	65	-	728	22	751	0	578	484	74.7	30.7	21	507	125	217	23.7	1073	374	9.9
A1.100	off/stbd	5-14/2430	11.1	114	7.4	649	67	717	-	609	571	81.8	30.8	21	707	154	241	34.9	1196	608	10.8
A2.100	off/stbd	5-14/2431	11.2	114	7.3	648	69	718	-	607	247	81.8	30.8	21	695	151	242	33	1195	570	8.6
A3.100	off/stbd	5-14/2432	11.2	117	7.3	647	70	718	-	608	369	82	30.8	21	704	154	242	34.2	1194	600	9.4
A1.100	off/port	5-14/2426	11.8	100	-	645	29	680	0	615	638	76.6	30.7	21	709	156	241	32.9	1190	540	10.8
A2.100	off/port	5-14/2427	11.8	110	-	652	26	676	0	618	660	76.8	30.7	21	707	156	240	32.4	1187	552	8.6
A3.100	off/port	5-14/2428	11.7	115	-	660	23	691	0	619	669	78.3	30.6	21	721	160	241	32.7	1189	564	9.4
B1.100	off/stbd	5-14/2449	10.9	109	7.6	659	70	730	-	622	308	82.1	30.8	22	712	156	241	34.4	1192	610	8.4
B2.100	off/stbd	5-14/2450	10.9	106	7.6	656	69	726	-	622	362	82.1	30.7	22	710	155	240	34.4	1192	592	8.6
B3.100	off/stbd	5-14/2451	10.9	106	7.5	656	69	725	-	622	195	82.1	30.8	22	719	157	240	35.4	1194	628	9.4
B1.100	off/port	5-14/2446	11.6	115	-	672	20	692	0	630	689	77.3	30.6	22	725	160	242	32.2	1188	566	8.4
B2.100	off/port	5-14/2447	11.5	120	-	674	19	698	0	632	745	76.8	30.6	22	752	167	242	33.1	1189	578	8.6
B3.100	off/port	5-14/2448	11.5	125	-	682	18	697	0	630	655	77.3	30.6	22	737	163	241	33.7	1189	572	9.4
B1.91	off/stbd	5-14/2440	11.5	78	7.1	684	86	771	-	573	174	82.6	30.8	21	482	116	216	24	1073	396	8
B2.91	off/stbd	5-14/2441	11.6	76	7	693	86	780	-	569	298	82	30.8	21	481	117	217	24.8	1071	400	8.1
B3.91	off/stbd	5-14/2442	11.5	78	7.1	690	86	777	-	572	135	83.4	30.8	21	489	119	217	24.8	1071	400	7.9
B1.91	off/port	5-14/2436	12	55	-	716	21	737	0	590	612	79	30.7	21	505	125	217	23.1	1074	374	8
B2.91	off/port	5-14/2437	12	65	-	723	20	750	0	589	605	80.3	30.6	21	505	124	216	23.7	1073	384	8.1
B3.91	off/port	5-14/2438	12	70	-	728	19	746	0	591	568	80.9	30.6	21	514	127	217	23.2	1074	374	7.9
B1.80	off/stbd	5-14/2420	12.7	62	6.2	658	105	764	-	474	166	80.1	30.8	21	311	86	192	17.1	946	264	10.1
B2.80	off/stbd	5-14/2421	12.7	61	6.2	660	106	766	-	476	162	80.6	30.8	21	311	86	191	17.7	946	264	9.9
B3.80	off/stbd	5-14/2422	12.7	61	6.2	658	105	764	-	479	105	82.1	30.8	21	312	87	192	17.9	946	264	10.6
B1.80	off/port	5-14/2417	13	70	-	716	27	735	0	498	370	79.6	30.7	21	330	94	191	17.1	942	248	10.1
B2.80	off/port	5-14/2418	13.1	65	-	704	27	733	0	489	390	80	30.7	21	331	94	191	16.9	939	248	9.9
B3.80	off/port	5-14/2419	13.2	65	-	711	27	739	0	491	322	79	30.6	21	332	94	191	16.8	942	248	10.6
B1.63	off/stbd	5-14/2411	15	76	4.5	496	99	596	-	369	189	80.2	30.8	21	133	46	150	10.6	744	122	8.4
B2.63	off/stbd	5-14/2412	15	76	4.5	504	99	603	-	367	192	80	30.8	21	137	48	150	10.8	743	126	8.5
B3.63	off/stbd	5-14/2413	14.9	76	4.6	505	101	606	-	365	173	80.1	30.8	21	135	48	151	11.2	741	126	8
B1.63	off/port	5-14/2407	15.2	85	-	548	28	580	0	399	301	81.1	30.7	21	149	56	152	10.7	750	120	8.4
B2.63	off/port	5-14/2409	15	85	-	532	28	562	0	394	280	81.6	30.7	21	158	55	152	10.7	749	124	8.5
B3.63	off/port	5-14/2410	15.1	85	-	526	27	547	0	388	279	81.4	30.7	21	161	55	152	11.1	751	124	8
C1.63	off/stbd	5-14/0112	14.7	70	4.7	530	99	630	-	366	206	82.7	30.9	22	147	52	151	11	746	130	10.6
C2.63	off/stbd	5-14/0113	14.7	71	4.7	528	100	629	-	368	202	81.9	30.8	22	134	47	151	11	746	130	9.7
C3.63	off/stbd	5-14/0114	14.8	71	4.7	515	99	615	-	366	201	80.6	30.8	22	137	48	151	11	747	130	10.3
C1.63	off/port	5-14/0108	15.1	80	-	535	22	559	0	377	288	79.6	30.6	22	152	57	150	10.5	740	120	10.6
C2.63	off/port	5-14/0109	15	80	-	537	24	560	0	377	286	79.3	30.6	22	149	56	150	10.5	749	120	9.7
C3.63	off/port	5-14/0110	15.1	80	-	534	24	559	0	376	292	80.1	30.6	22	149	56	150	10.5	740	120	10.3
C1.100	off/stbd	5-14/0120	11	110	7.4	638	73	712	-	602	389	81.5	30.9	22	697	152	240	33.8	1189	592	14.7
C2.100	off/stbd	5-14/0121	11	111	7.4	637	75	712	-	608	293	81.5	30.9	22	684	150	240	33.1	1189	578	14

C3.100	off/stbd	5-14/0122	11.1	113	7.4	633	75	708	-	608	286	81.5	30.8	22	684	150	240	33.2	1190	566	13.2
C1 100	off/port	5-14/0117	11.6	110	-	645	25	673	0	612	725	78.8	30.6	22	729	160	240	32.8	1188	566	14.7
C2 100	off/port	5-14/0118	11 6	110	-	662	22	682	0	616	788	79.8	30.6	22	730	161	240	32.8	1190	566	14
C3.100	off/port	5-14/0119	11.5	115	-	671	19	689	0	619	726	79.5	30.6	22	725	160	240	32.8	1189	564	13.2
C1.91	off/stbd	5-14/0131	11.6	73	7	703	75	778	-	563	428	82.4	30.9	22	480	117	217	24.7	1071	400	12.4
C2.91	off/stbd	5-14/0132	11.5	80	7.1	700	85	785	-	567	236	81.6	30.8	22	481	117	217	23.9	1069	400	11.8
C3 91	off/stbd	5-14/0133	11.6	78	7	684	87	772	-	565	161	82	30.9	22	471	114	217	24.2	1071	394	12.5
C1.91	off/port	5-14/0125	12.1	65	-	723	19	742	0	588	532	77.5	30.6	22	510	126	217	23.4	1071	378	12.4
C2.91	off/port	5-14/0127	12	75	-	723	18	738	0	588	540	78.6	30.6	22	518	126	217	23.7	1072	390	11.8
C3.91	off/port	5-14/0129	12.1	75	-	727	18	747	0	587	614	75.9	30.6	22	512	126	217	23.4	1071	378	12.5
C1.80	off/stbd	5-14/0139	12.7	59	6.2	674	106	780	-	492	109	82	30.9	22	310	85	191	17.2	945	258	10.6
C2.80	off/stbd	5-14/0140	12.7	64	6.2	669	106	775	-	491	172	81.5	30.9	22	317	87	191	17.4	945	258	10.5
C3.80	off/stbd	-	-	-	-	-	-	-	-	-	176	82.1	30.8	22	309	85	191	17.2	945	254	11.4
C1.80	off/port	5-14/0136	12.9	55	-	731	21	741	0	523	441	76.8	30.6	22	359	100	194	17.6	956	258	10.6
C2.80	off/port	5-14/0137	12.9	60	-	725	21	748	0	525	443	79	30.6	22	355	100	194	17.4	955	262	10.5
C3.80	off/port	5-14/0138	12 8	65	-	719	21	745	0	525	437	77	30.6	22	356	100	194	17.1	965	258	11.4